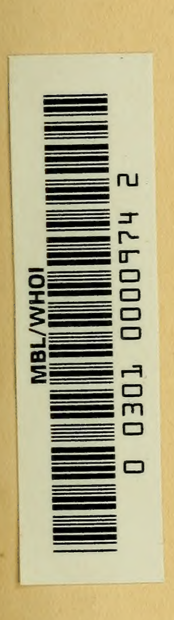
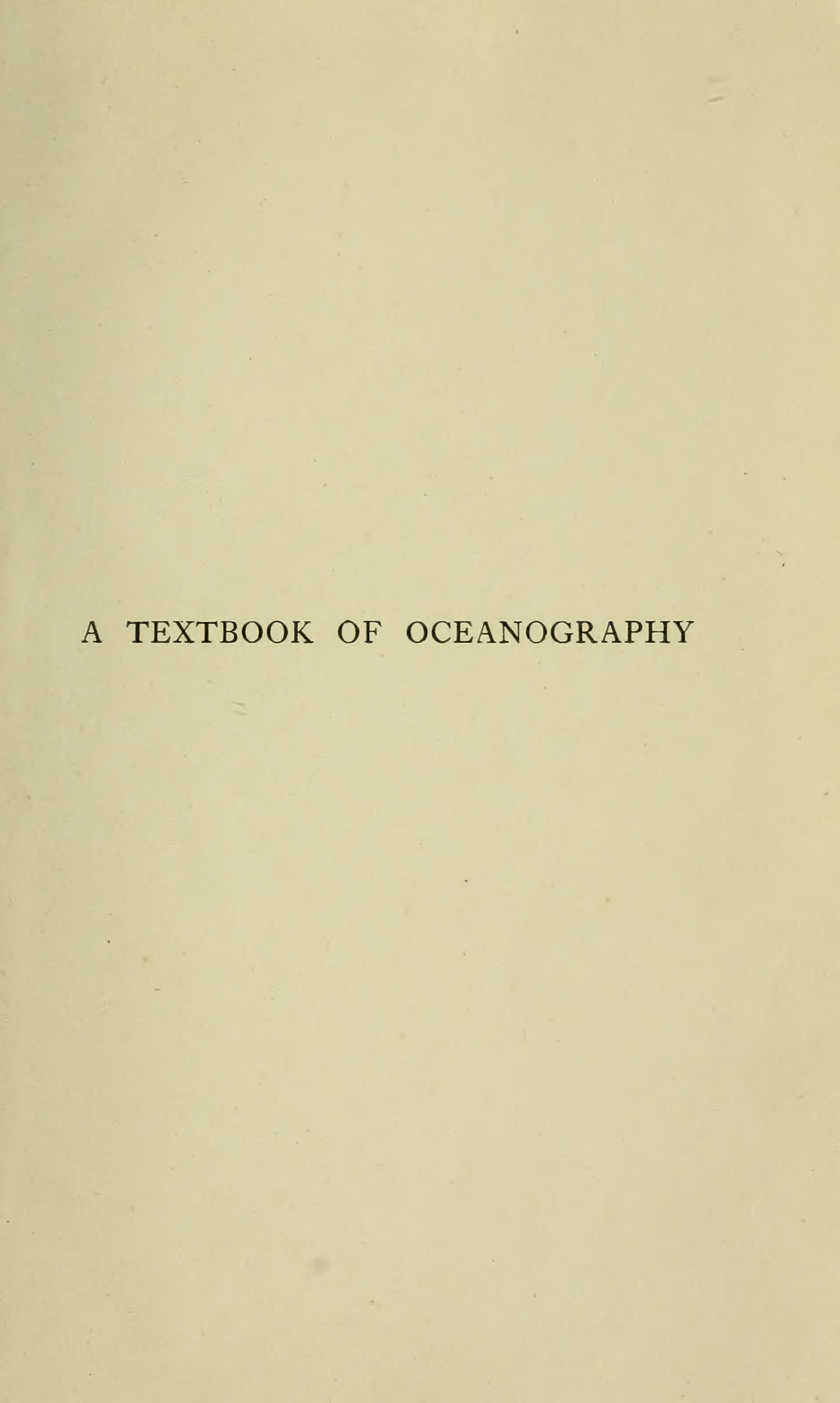
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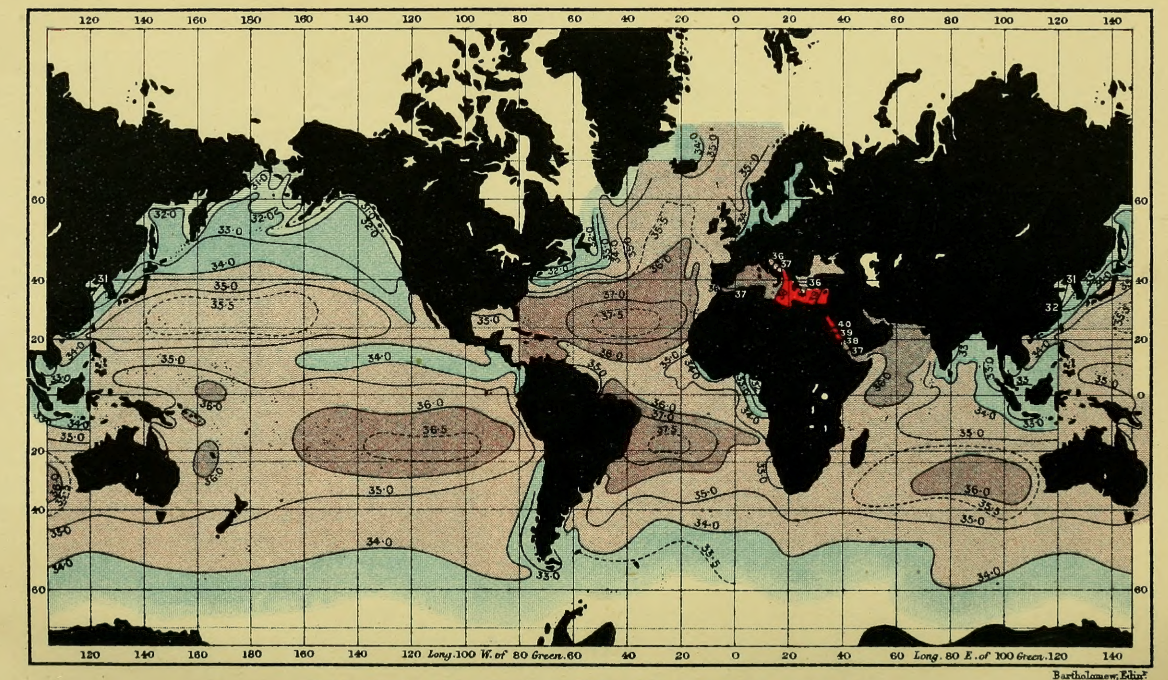
J. T. JENKINS




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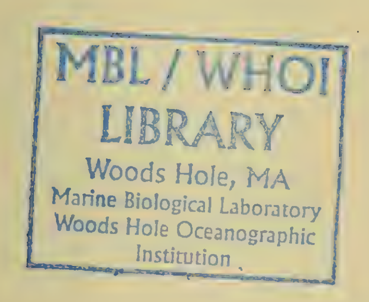
OF

OCEANOGRAPHY

BY

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LONDON

CONSTABLE & CO. LTD.

10-12 ORANGE STREET, W.C. 2

1921

PREFACE

In spite of the great interest that maritime questions have for the English-speaking nations, there is no modern textbook in English on the subject of oceanography.

Considerable progress has recently been made in the teaching of geography, which is now a degree course at many of our Universities. Although there are many textbooks and manuals on navigational subjects, some of which are published under Government or departmental auspices, it cannot be claimed for these works that their oceanographical (as distinguished from their navigational) instruction is at all up to date. In fact, in most of these works such questions as, *e.g.*, ocean currents are dealt with regardless of modern methods of scientific investigation, and apparently the authors are simply content to copy from older textbooks on the subject. Consequently there is a gap which it is hoped may be filled by a book which, without being unduly technical or mathematical, will give the student an opportunity of becoming acquainted with modern methods of oceanographical research and their chief results. This book has been designed to meet the requirements of the higher forms of schools, of teachers in training, and of students attending a school of geography at one of the Universities, as well as intending naval and mercantile marine officers, since, although a textbook of oceanography can hardly be regarded as an aid to navigation, it should contain much of interest to seafarers. The book should be read with the aid of an atlas, since it is impossible, without unduly enlarging the scope of the book, to provide charts and plans to illustrate all the points dealt with. References are not (in general) given

in the form of foot-notes, but a small bibliography of the more important publications in the English language is printed as an Appendix.

Two criticisms will probably occur to many readers, so it may be worth while to attempt to meet them here. In the first place there is no uniformity in reference to depths, temperatures, etc.; the metric system is sometimes used, at other times the depths are given in fathoms. Theoretically it would have been better to have used the metric system only. Actually the British or American seafarers' concept of a fathom is more vivid than that of a metre. Until the metre is universally adopted—*e.g.*, in the British Admiralty charts—it is inexpedient to ignore the fathom. The difficulty is, however, more apparent than real, since the table for conversion (p. 198) is available.

Objection may secondly be taken to the didactic style. This style is inevitable if the information is to be compressed within reasonable compass.

My best thanks are due to Mr. Wade for friendly assistance in the preparation of the text figures; to Dr. E. J. Allen, of the Marine Biological Laboratory at Plymouth, for the loan of process blocks illustrating the hydrographical work of the International Council; and to Messrs. J. Engelhorn's Nachfolger of Stuttgart for permission to use certain illustrations taken from Krümmel's "Handbuch der Ozeanographie."

CONTENTS

CHAPTER I

CHAPTER II

CHAPTER III

CHAPTER IV

CHAPTER V

APPENDICES



LIST OF ILLUSTRATIONS

A TEXTBOOK OF OCEANOGRAPHY

CHAPTER I

Introduction

The seas form so large a part of the environment of mankind that the reasoned description of their great area and contents is a subject of the very first importance. The main features of the seas and oceans of the globe affect human life and its problems in endless ways. The oceans exercise a profound influence over climate and vegetation, the possibilities of cultivation and human settlement. Oceanic movements, both tidal and non-tidal, affect the harbours of the globe and our maritime intercourse, and had still more intimate bearings on that intercourse in the days before the introduction of steam as a means of the propulsion of vessels and the era of great engineering feats such as ship-canal construction. These movements also affect the migrations of fish and cetacea, and so influence fisheries and the growth of sea-power.

Pettersson and others have described the important influence of secular variation of tides and currents upon changes of climate within historic times, and consequently upon the rise and fall of human societies. The story of the seas of the past is recorded imperfectly in the sedimentary rocks; even the few facts known throw important light upon diverse scientific problems.

At the outset it is essential to understand that the great water masses are not alike in condition or constitution, nor is any one of them homogeneous. Just as meteorologists are certain that masses of air of different temperature and water-

content mix with difficulty, so oceanographers draw attention to the different layers and volumes of water in one and the same ocean.

This fact may easily be observed, since on a fine day after heavy rain one may notice at the mouth of a river the fresh muddy water spreading out at the surface over the blue-green salt water. The wake of a steamer makes a narrow green lane through this surface water. In the main oceans there is similarly a surface layer (often of considerable depth) in which the sun-warmed waters are full of plant and animal life, this layer being quite distinct from the deeper and colder waters, often of Polar origin. In this surface oceanic layer the plant and animal life consists of two main groups—drifting organisms, to which the term "plankton" is applied; and swimming organisms—*e.g.*, fish and cetacea—capable of making headway against a current; these are called "nekton."

The stream of relatively fresh water which flows out continuously through the Bosporus and Dardanelles above the smaller counter-stream of salter water which flows in from the Ægean did much to determine the site of Troy on the peninsula to the south of the Dardanelles. The roads across that peninsula enabled prehistoric traders to avoid the current of the Dardanelles, which was dangerous in the days of small ships propelled by square sails or oars. The deep blue Atlantic water which floods the English Channel in autumn makes a striking colour contrast to the rich red-brown of the dying bracken on the cliffs. At other seasons our shores are washed by vivid blue water from the Iberian coasts, perhaps even by Mediterranean water, and in these waters float strange organisms of warmer climes, such as Physalia, the "Portuguese man-of-war."

The differences in physical characters, mainly salinity and temperature, make the oceans a complex of water masses of varying characteristics—masses which collide, but only commingle with difficulty.

These masses of water rise and sink in accordance with

changes in temperature and salinity. At the entrance to the Baltic there is an upper layer of colder and fresher water; below it a warmer salter layer.

The movements of these large water masses relatively to one another and to the land afford the oceanographer an endless field for research. Oceanic circulation due to differences between the physical characters of masses of sea-water is only one phase of the problem to be studied. The tidal movements, varying in fortnightly, half-yearly, and secular cycles of many kinds, many of them as yet imperfectly known, add to the complexity and interest of the story. The influence of prevailing winds on ocean movements, so far as surface waters are concerned, is another aspect of oceanographical research, with many difficulties that some of the older textbooks have overlooked completely.

Probably all the large scale movements of the waters of the ocean are profoundly affected by the contour of the ocean floor and the presence of land; this, again, is a subject for further research. The deep abysses just off the lines of high volcanic influence and more or less parallel with them (*e.g.*, off Japan and the South American Cordilleras); the Wyville-Thomson ridge connecting the north of Scotland and Iceland, of great interest in the evolution of the Atlantic; the Grand Banks of Newfoundland, with the problems of their physical character, all suggest important aspects of study along the line of junction between geography, geology, and oceanography. The conformation of the coastal sea-floor gives an opening into questions of the dynamics of tidal and other waves, and is of direct practical importance in connection with questions of harbour construction and protection. The details of local sea and coastal currents have their bearing on the characteristics of shore deposits and the building and erosion of our coasts.

All this interplay of physical influences has an endless correlation in the world of life. The herring of Cardigan Bay enter the bay from the south, and first spawn when they feel the influence of the fresh water of the Dovey estuary. Again,

the coastal plankton varies according to whether the rivers discharging into the sea are fed by spring or autumn floods. This makes it worth while to study the variation of the plankton from month to month, so as to draw inferences as to the movements of fish to and from the coast.

It is, however, by no means a case of a simple chain of cause and effect. Migrations of fish are not simply affected by plankton and hydrographic changes. The necessities of the life of our important food fish include a suitable place for reproduction and for the growth of the delicate younger stages of life, and this makes the story more complex. The avoidance of enemies and the feeding of fish on one another are also factors to be taken into consideration.

Oceanography is thus concerned with the elucidation of many intricate and complex problems of physical and biological nature, and an increased knowledge of the subject contributes in many ways not only to purely scientific questions such as the progress of evolution, but also to such practical problems as the wiser and less destructive utilisation of great natural assets such as marine fish and cetacea.

The Extent of the Ocean.

Broadly speaking, the surface of the world was thought to be composed of three parts of water to one part of land.

Recent Polar explorations, particularly in South Polar regions, have revealed the existence of enormous land masses —for instance, Victoria Land and Graham Land. If we take these into account, they will appreciably reduce the difference previously thought to exist between the land and water surface of the globe. Even so the most recent calculations give the ratio of land to water as 1 : 2·43, or, expressed as percentages, 29·2 : 70·8. So that it is approximately correct to say that the oceans are two and a half times as extensive as the land masses of the earth's surface.

The division of the world into water and land plays an

important part in ancient cosmogonies, and nearly all the myths and religions of primitive peoples contain accounts of the origin of land and water, even where such people have been for generations shut off from the sea—*e.g.*, the Sonthals of Chota Nagpore, India. Some of the older theorists believed that the land surface of the globe must exceed the water surface, since the Creator made the world for human habitation.

Mercator (1569) put forward a theory of equilibrium according to which the land masses of the Northern and Southern Hemispheres balance one another, and also the land and water areas of the globe were approximately equal, as, indeed, was shown on his later charts.

The first idea was shaken by the voyages of Tasman, who was sent out in 1642 on an expedition for the discovery of the "Great South Land," and finally exploded by Cook's great voyage of discovery.

The earliest serious attempts to measure the extent of the land and water surfaces of the globe were those of English investigators.

Dr. Long in 1742 estimated the ratio of land to water to be 1 to 2·81, or 26 to 74 per cent. At that time the Polar regions were not at all well known. In 1837 Professor Rigaud of Oxford made a similar calculation, and estimated the ratio of land to water to be 26·6 to 73·4 per cent.

It would be an interesting subject for research to determine the history of the ideas of land and water distribution on the earth's surface.

The distribution of land and water on the surface of the globe is most irregular.

North of the Equator, instead of the average 70·8 per cent. water, we find only 60·7; whereas south of the Equator the water average is 80·9. It follows that 43 per cent. of the seas and oceans are in the Northern Hemisphere, 57 per cent. in the Southern Hemisphere.

If we divide the earth's surface into zones of 5° of latitude, it is only between 15° and 20° N. that we find the distribution

of land and water corresponding to the average distribution for the whole of the earth's surface.

The sea surface is much below the average between 20° and 75° N. Lat., and between 45° and 70° N. the sea does not cover half the earth's surface. In the Arctic Circle the land occupies three-quarters of the surface. In tropical regions the sea occupies most space, taking up three-quarters of the surface. South of 35° S. Lat., where the African and Australian Continents end, the sea covers nine-tenths of the earth's surface. Between 56° and 60° S. there is, except for the South Sandwich Islands, nothing but water.

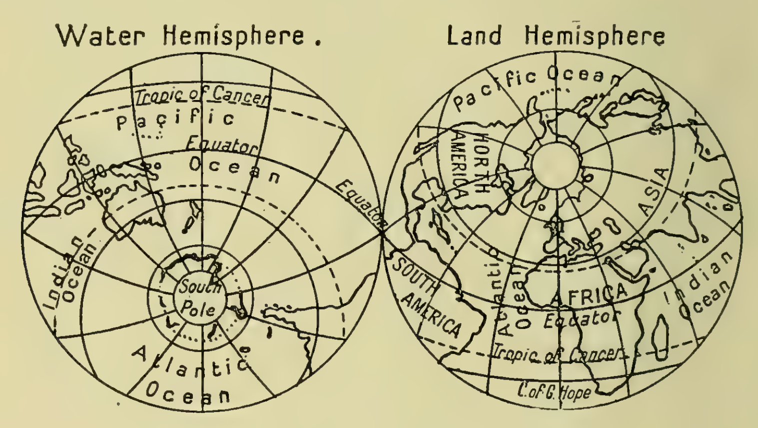


FIG. 1.—THE LAND AND WATER HEMISPHERES.

The Old World contains 62·1 per cent. and the New World 81·2 per cent. water.

The west and south parts of the earth contain the great water areas, the east and north the great land areas. It is possible to divide the surface of the earth up into two hemispheres, so that one contains the maximum area of land, the other of water. These are the so-called land and water hemispheres. According to recent measurements, the centre of the land hemisphere is on the coast of France, near Croisic, at the mouth of the Loire. The centre of the water hemisphere lies in the Pacific Ocean south-east of New Zealand.

The boundary of the so-called land hemisphere is a circle running through the meridian of Greenwich in 42° S., including Africa and Madagascar; then running between the Nicobars and Sumatra north-easterly, crossing the isthmus of Krah in 10° N.; thence between Siam and Annam, from Hong-Kong to Foochow along the Chinese coast, cutting through Japan, so that Nagasaki belongs to the land hemisphere and Tokio to the water hemisphere. It then cuts the meridian of 180° W. in 42° N., takes in the whole of North America, passing Albemarle Island in the Galapagos group, and reaches the South American Continent at Arica. Even so the water exceeds the land in the ratio of 52·7 per cent. to 47·3 per cent.

The so-called water hemisphere has 90·5 per cent. water to 9·5 per cent. land.

The land surface of the globe consists really of four large continental islands. There are three really great oceans—the Atlantic, Indian, and Pacific. The so-called Arctic Ocean is really a sea, and the Antarctic inseparable from the other three. There is a wide connection between the southern extremities of the three great oceans.

Between the Atlantic and Pacific from Cape Horn to the Antarctic Continent not less than 540 miles; between the Indian and the Atlantic from Cape Town to the Antarctic (Enderbyland) 189 miles; between the Indian and Pacific from the south point of Tasmania to Wilkes Land 1,350 miles.

Consequently the great oceans are in direct communication with one another. There are three main oceans—Atlantic, Pacific, and Indian. The Arctic Ocean is really a sea.

Opinions differ as to whether an Antarctic Ocean should be separated off from the other three. The majority of oceanographers seem to be against it. In maps where Mercator's projection is used an entirely false impression of the so-called "Antarctic Ocean" is given.

Classification of the Oceans and Seas.

1. Position.
2. Size.
3. Form.
4. Water salinity.
5. Tides and currents.
6. Origin.

1. *Position, or Situation.*

The nomenclature of the oceans and seas is quite unscientific, but the names are so well known and so firmly fixed there is no object in changing them.

To give one example. Seas of a mediterranean type have the following names—Mediterranean Sea, Persian Gulf, Hudson Bay, Gulf of Mexico, and Arctic Ocean. In this type the sea penetrates deeply into the land, and access to the ocean is by a narrow strait or straits. Seas of this kind have a marked individuality, as will be seen later. A second type of sea is one with access to the ocean by means of a fairly wide connection. For instance, the North Sea, English Channel, Gulf of St. Lawrence, Sea of Okhotsk, Gulf of California, and Bass Straits.

Several attempts have been made to classify seas according to their situation. The Germans have excelled at this, and we get Randmeere, Nebenmeere, Vormeere, Durchgangsmeere, and so on.

2. *Classification according to Size.*

This is the chief difference between oceans and seas. The so-called Arctic Ocean has an area of 14 million square kilometres, whereas the Indian Ocean's area is 73, the Atlantic 82, and the Pacific 166 million square kilometres. (A square kilometer = 0·386 of a square mile.)

For comparison : The area of the Mediterranean is 3 million square kilometres, Bering Sea 2⅓, Sea of Okhotsk 1½, and the North Sea ½ million square kilometres.

Estimates of the volume show even greater differences. The volume of the Arctic Ocean is one-twentieth that of the Atlantic and one-forty-second that of the Pacific.

3. *Classification according to Form or Configuration.*

Three main types: Oceans; seas narrowly connected therewith; seas widely connected therewith.

4. *Salinity.*

The great volume of the open oceans consists of water of salinity 35 per mille, and except in a narrow band round the coasts the extreme variation may be said to be between 34 and $37\frac{1}{2}$ per mille.

There is a marked difference between the open ocean and the seas, since the latter are usually below or above the normal, the chief exception being the Caribbean Sea—Gulf of Mexico, which stand in close connection by means of strong currents with the open Atlantic.

Subtropical seas usually have water above normal salinity—*e.g.*, the Mediterranean, the Red Sea, and the Persian Gulf. These lie in regions of relatively dry climate, so there is strong evaporation due to high temperature and low rainfall. The Gulf of California is also possessed of water of higher salinity than the neighbouring Pacific.

Salinity below the normal is met with in tropical waters with excessive rainfall, or in temperate waters where, owing to large rivers and excessive land drainage, the dilution is considerable.

Example of the former, sea between North Australia and South-East Asia—*e.g.*, Banda Sea.

Example of the latter sea, the Baltic Sea and Hudson Bay.

The variation of the salinity from the oceanic type depends naturally to some extent on the size (*e.g.*, breadth and depth) of the connecting passage between the sea and the ocean. With a narrow entrance we get extreme variation—*e.g.*, on the one

hand the Red Sea with 41 and the Mediterranean with 40 per mille, and the Baltic with from 1 to 15 per mille.

EXAMPLES OF SEAS, CLASSIFIED ACCORDING TO SALINITY.

I. Salinity Above Normal.	II. Normal.	III. Below Normal.
Red Sea (37-41).	Caribbean-Mexico (35-36).	(a) *Slightly Under.*
Persian Gulf (37-38).	Bass Straits (35½).	Arctic "Ocean" (20-35).
Mediterranean (37-39).	Gulf of California (35-35½).	North Australian Sea (33-34).
		Bering Sea (28-33).
		Sea of Okhotsk (30-32).
		Sea of Japan (30-34).
		China Sea (25-35).
		Andaman Sea (30-32).
		North Sea (31-35).
		English Channel (Irish Section) (32-35).
		Gulf of St. Lawrence (30-32).
		(b) *Much Below.*
		Baltic Sea (3-15).
		Hudson Bay.

A classification of seas according to temperatures is also possible.

5. *Classification according to Movements—i.e., Currents.*

The open ocean is the region of the origin of tidal movements. Tides are met with in enclosed seas only under certain special circumstances. Enclosed seas with narrow entrances—*e.g.*, the Mediterranean—are only subject to tidal waves near the entrance. The tidal effect diminishes the further one gets from the entrance.

Broadly speaking, the ocean is the origin of the great independent tidal waves; the seas, on the other hand, are the regions of the dependent tides and currents. Currents are dealt with in greater detail below.

SCHEME OF CLASSIFICATION—

1. Oceans with independent tidal waves and currents.
2. Seas with dependent systems.
    (A.) Dependent, influenced by ocean tidal streams and currents:
        (*a*) With through flowing current—Caribbean Sea, Bass Straits.
        (*b*) With partly through flowing current of oceanic characteristics—Red Sea, Australasian Sea, China Sea, Irish Sea and Channel.
        Practically no current—Gulf of California and Persian Gulf.
        (*c*) Current partly of oceanic origin, partly meteorological — Mediterranean, Japan Sea, Sea of Okhotsk, Bering Sea.
    (B.) Dependent, but mainly due to influence of land drainage—Arctic "Ocean," Baltic, Hudson Bay, Gulf of St. Lawrence.

6. *Classification according to Origin.*

An enclosed sea may be compared to a vessel, such as a kettle, containing water. We are not concerned with the nature of the enclosing material so much as with the nature of the contents. It is difficult for a land-dweller to take up the suitable point of view, which would be that of an educated seal, regarding the sea as all-important, and the land as a mere excrescence containing the sea.

Suess has classified seas according to their origin, but geological knowledge is not sufficiently advanced to enable us to give a complete classification of seas according to their origin.

The present shape of the earth is due to a shrinkage caused by cooling. The oceans, with their enormous depths, are the results of contraction of the earth's radius at those points.

Probably the present situation of the great oceans has

endured at least since Mesozoic times,* but the seas of Mediterranean type are, geologically speaking, young seas, many of them, in fact, in spite of relatively considerable depths, are of tertiary and some even of post-glacial origin.

The classification of great water areas according to origin gives us two main types :

1. The deep sinkings between the main masses of the earth's continents—*i.e.*, the oceans. These are of great antiquity geologically speaking, and have been permanent since their origin.

2. The seas formed at the edges of the continents. They are of recent origin geologically, and have changed much in recent times. They are of two main types :

(1) Formed by sinking of the continental crust.

(2) Formed in breaking of the waters of the oceans by dislocation of the earth's crust.

Seas of the former type are shallow, and the present sea bottom owes its configuration to previous aerial denudation in the main. Examples : The Baltic, Hudson Bay ; probably the southern North Sea is also of this type.

The second type resulting from dislocation of the earth's crust. Example : The Red Sea.

Gulfs and Bays.—These are difficult to classify from an oceanographic standpoint, since the nomenclature is very confused. Bays, bights, and gulfs have slightly different form as a rule, though the three names have been applied at different times to the same—*e.g.*, Bay of Biscay. It is now impossible to rectify this nomenclature.

Bays and gulfs are, broadly speaking, of two main types :

(*a*) Oceanic.

(*b*) Mediterranean—*i.e.*, communicating with the ocean indirectly through an enclosed or partially enclosed sea.

The diversity in form, size, and so on, is so great that any

* Though their connections have altered—*e.g.*, the Wyville-Thomson ridge may, since Mesozoic times, have formed a dry-land connection between America and Europe.

classification according to that adopted for seas does not help us much.

Straits.—Narrow connections between different sea areas, generally between parallel coast-lines.

(*a*) First type, formed by dislocation of earth's crust. Longitudinal type: the strait is parallel to the chief line of dislocation—*e.g.*, Bab-el-Mandeb. Transverse type: the strait is perpendicular to the main line of dislocation—*e.g.*, Straits of Gibraltar.

(*b*) Straits formed by marine erosion: Straits of Dover.

(*c*) Straits formed by sinking of the earth's crust and consequent inflowing of the sea. To this class belong most straits of shallow seas—*e.g.*, Bering, Formosa, and Torres Straits.

Sea-Level.

If the earth's surface were entirely covered by water of equal temperature, then a perfect rotation ellipsoid would be formed, and all meridians of longitude would be equal ellipses, and all parallels of latitude perfect and concentric circles. Everywhere the deep sea lead would be perpendicular to the sea surface, and at the same time in the line of the earth's radius.

On such an ideal globe the local relation of centrifugal force would be proportional to the gravitational force.

In the actual globe land masses break through the water, and immediately cause a disturbance from the ideal condition described. Since land is 2·6 (or according to some theories 2·8) times heavier than water, the lead when cast in waters near the land must deviate towards the land in response to the attraction of gravity. The surface of the sea, which is perpendicular to the direction of the lead-line, is therefore disturbed from the ideal, and takes up a different position to that it would occupy were no land present. The sea-level is therefore depressed in mid-oceanic areas and elevated near the coasts of the continents.

This elevation of the sea surface near the land is termed the "continental wave." Not only is the surface of the sea

irregular near the land, but also in the open ocean a corresponding irregularity is met with, since each depression of the ocean bottom is correlated with a depression of the sea-level. These irregularities of sea-level can be determined by experiment or can be calculated from theoretical considerations. The pendulum is used for this determination. If a pendulum be swung on the same parallel of latitude over the land and then over the sea where there is a marked depression of the ocean floor, it should swing more quickly in the latter position, where it is nearer the earth's centre. Records of the seconds pendulum taken off the Bonin Islands (Japan) and the north coast of Brazil showed, according to Listing, a difference in level and consequently a height for the continental wave of 2 kilometres. This estimate is almost certainly erroneous and far too high.

More modern attempts with Sterneck's half-second pendulum are certainly more accurate, and the best of these were recorded by Scott Hansen of the *Fram* when Nansen's ship was frozen in in the Arctic (1894-95). Scott Hansen found in areas of the sea where the depth was 1,640 fathoms (3,000 metres) that the periodicity of Sterneck's pendulum only departed very little from the normal, and it is very probable that this is true, not only for the Arctic "Ocean," but also for the larger oceans.

Comparisons of the pressure by the mercurial barometer and observations made with delicate boiling-point thermometers on the South Atlantic between Lisbon and Bahia show the gravity on this route is nearly normal.

Temporary differences in sea-level are due to a number of causes, among which may be mentioned the sun's rays; the influence of large volumes of water derived from land drainage, very noticeable at Kronstadt (Gulf of Finland) and Odessa; prevailing winds; and the barometric pressure.

The level of the sea varies with the pressure of the air; every movement of the mercurial barometer is correlated with a change in the sea-level. Sir James Ross, who wintered at Port Leopold in 1848, made hourly observations of the height

of the barometer and the depth of water in the harbour. He found extremes for the former were 767·75 and 750·79 millimetres, corresponding to the water depths of 6,309 and 6,538 millimetres. Here the variation corresponds closely to the difference in specific gravity between mercury and the sea-water—that is, according to the above records, = 13·5.

Careful modern coastal surveys show no marked differences in sea-level; those recorded do not exceed half a metre. Surveys connecting up the coast of the Atlantic near New York with that of the Pacific near Seattle show a difference of only 187 millimetres, which lies between the limits of error over such a long distance (7,400 kilometres).

Hypsographical Curve of the Earth's Surface.

The investigations of modern oceanographers have given us a fairly comprehensive knowledge of the nature and extent of the sea bottom, its depth, physical constituents, and animal life. Generally speaking, the great oceans are far from shallow, and the volume occupied by water below sea-level greatly exceeds the volume of land above sea-level. If the land above sea-level were tipped into the sea it would only partially displace the sea-water (see Fig. 2).

The greatest oceanic depths far exceed the heights of the highest mountains. Nero Deep, off the island of Guam (Marianne or Ladrone Islands, North Pacific) is 5,270 fathoms or 31,620 feet deep. Mount Everest, the highest mountain in the world, is 29,000 feet high. Nero Deep is, however, an extensive depression, and an area equivalent to the islands of Sardinia and Sicily lies below 3,830 fathoms.

The hypsographical curve gives an idea of the relationships of land to water at the earth's surface. It shows us the relatively small area of sea bottom within the 200-metre line and below 5,750 metres. The descent from the continental shelf edge in about 200 metres to a depth of 3,000 is extremely sharp, and between 1,000 and 3,000 metres there is only 14·8

per cent. of the sea bottom. The land surface over 4,000 metres high is only of 3 million square kilometres extent; that over 5,000 metres only ½ million.

The sea bottom below 4,000 metres depth is 185 million square kilometres—that is, 36 million more than the whole

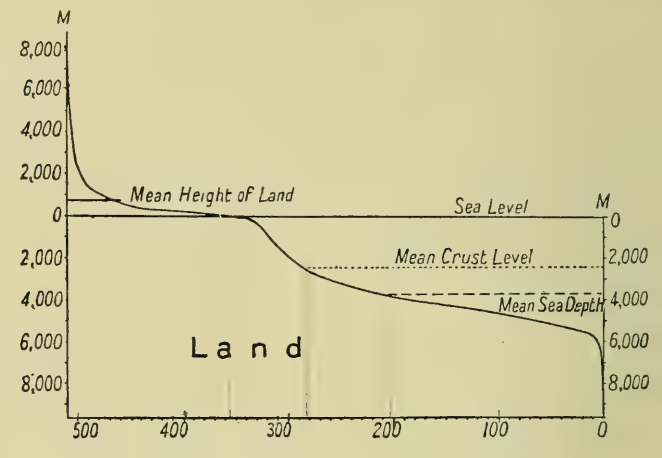


Fig. 2.—Hypsographical Curve of the Earth's Surface.

surface of dry land. Depths below 5,000 metres comprise 72 million square kilometres, nearly half the dry land area. Nearly 5½ million square kilometres lie below the 6,000-metre line.

The oceans represent, therefore, tremendous cavities in the earth's surface.

The General Features of the Ocean Bottom.

The great ocean bottoms are not concave, but convex, as portions of a spherical surface should be. Concavities are only met with exceptionally; they are especially characteristic of continental seas. The bed of the ocean consists for the most part of flat plains of enormous extent. The least deviation from the horizontal appreciable to the naked eye is one in 200 or 0° 17′, and this slope is seldom met with in the beds of the great oceans.

The British telegraph cable steamers found extremely flat surfaces in the Atlantic. Between 46° and 38½° W. the *Britannia* found in only one instance a slope which would be appreciable to the naked eye (30′ 44″), and for the whole of this distance the slope was only 9′ 42″. Flat stretches of this kind and extent are not met with on dry land. Agassiz found in the South Pacific on a course of 3,200 miles the greatest difference in depth to be only 400 fathoms—that is, on the average 9 inches to the mile. Similar results have been obtained by American cable steamers in the North Pacific; for 100 miles between 173° and 175° E. Long. the greatest deviation from the mean depth of 5,938 metres was only +38 and −38 metres. Again, between 155° and 160° E. Long. the greatest deviation from the mean of 5,790 metres was only +103 and −112 metres. The great success of the submarine telegraph cables is in part due to this flat surface of the ocean bottom. Only near the land in the neighbourhood of the continental shelfs is there any steep and broken slope, and it is precisely here that the breaks in the telegraph cable mainly occur. In the North Sea west of Heligoland five-mile areas show a difference in depth of about 2·8 metres, a flatness which is never met with on land surfaces.

Even when the flatness of the land surface approaches that of the sea bottom, there are in reality striking differences. A profile of the mid-European plain would show quite a number of sharp folds, whereas a profile of a similar area in the bottom of the North Atlantic would show at most a gentle swell or ridge. Not only is the ocean bottom free from the denudation caused on land by atmospheric influence, but it is also, apart from a narrow zone in continental regions, free from those dislocations of the earth's crust which have been and are responsible for so great a diversity on the land surface of the globe.

The steepest submarine slopes are those which support oceanic islands. St. Helena has submarine slopes of from 38½ to 40°; Tristan D'Acunha, 33½°; and St. Paul, for short slopes, as much as 62°. Many of these oceanic islands are due

to volcanic action; in some cases this action has not been sufficiently pronounced to build up an island, so we have the phenomenon of "submarine peaks." A large number of these appear on the charts; some of them are so near the surface as to give anchorage to ships. For the most part, these submarine peaks were discovered by cable steamers; some of them are doubtless due to errors in soundings, and will disappear on further investigation. Six of these peaks are found close together in the angle between Gibraltar, Madeira, and the Canary Islands. In many cases the volcanic origin of these peaks has been proved by the nature of the bottom as revealed by the deep-sea lead. In some instances coral structures are identified, more rarely mud. Some of these peaks have been recorded once only, and the most careful survey has failed to identify them a second time. According to Littlehales, the probability of finding a small submarine peak of a square metre surface is only 1 in 6,173.

Steep slopes are also found on the continental rim. According to the hypsographical curve, the area between 1,000, 2,000, and 3,000 metres is relatively very small, and from this it follows that there must be steep slopes in these soundings. At the north end of the Bay of Biscay, where the continental shelf ends, there is an Alpine relief to the sea bottom. Thoulet in 1895 spoke of this region as "une véritable falaise."

The naming of the characteristic features of the ocean floor is very confused. The oldest names, applied, however, only to shallow seas, are the "Banks" and "Grounds" of the fishermen—*e.g.*, the Dogger Bank and the Oyster Grounds. The older oceanic names are those of the Atlantic: the Dolphin Ridge of the U.S. Brig *Dolphin*, and the Challenger Ridge of the *Challenger*. The earliest bottom chart of the Pacific contains a number of names derived from the exploring ships and their scientific leaders. Other systems rely on geographical names exclusively.

Sir John Murray adopted a combination of these methods,

occasionally using purely geographical terms, at other times names of ships or oceanographers. To depths exceeding 3,000 fathoms he applied the term "Deeps," and these were named exclusively after persons.

In some instances more than one system has been used for the same ocean, much confusion thereby being caused. For the Pacific Ocean in particular there are four distinct systems of naming the features of the ocean floor. Even at the present time there is no general agreement amongst oceanographers as to the nomenclature to be adopted.

The relatively shallow area bounding continental masses is termed the "Continental Shelf." This shelf belongs to, and may be considered as a part of, the continental land. The seaward boundary of this shelf may be taken, in the majority of cases, to be the 100-fathom line, where there is usually a sharp descent to great oceanic depths. In recent geological periods this shelf formed a part of the dry continental land. In high latitudes this shelf is characterised by the presence of erratic boulders due to the Ice Age; in tropical areas by the growth of corals. The continental shelf is in general free from the traces of volcanic action. In addition to the true continental shelf there are pseudo-continental shelfs, entirely cut off by deep water from the main continental masses. Of these the Seychelles may be taken as an example. The continental shelf is of considerable economic importance, since it constitutes the spawning-ground of all marine fish of economic importance, and on it the great sea fisheries of the world are carried on.

The continental shelf forms about 8 per cent. of the sea area. The sea bottom here is composed of material derived from the land masses. All changes in level of 100 fathoms above or below sea-level have taken place in recent geological times. Only occasionally is the continental shelf extremely narrow—*e.g.*, the west coast of South America between 35° and 14° S. Usually in such localities the land exhibits the characteristics of a raised shelf.

Two theories have been put forward to account for the origin of the continental shelf. According to the first, it is due solely to the denudation of the land; but if that were the case we should expect the sediments to exhibit a progressive diminution of size of the component particles as we recede from the land to the open sea. This is, however, by no means the case.

The second theory accounts for the origin of the continental shelf by ascribing it exclusively to the effects of marine erosion.

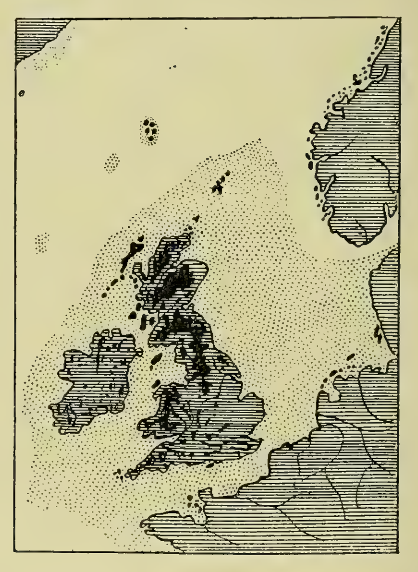


Fig. 3.—The British Isles and the Continental Shelf.

On this theory we should expect the widest shelf areas to be found where storms and waves are at their maximum. This is not the case, since land breezes prevail off the east coast of North America from the Straits of Belle Isle southwards to Cape Hatteras, where the continental shelf is wide and well marked.

The British Continental Shelf.—Off the south of Ireland and at the entrance to the English Channel the banks run parallel to one another in a direction roughly from north-east

to south-west—that is, in a similar direction to the mountain ridges in the south-west of Ireland, Cornwall, and Brittany. The southern part of the North Sea is only recently derived from the land, certainly since the Ice Age.

Here the trawlers not infrequently take in their trawl-nets bones of the mammoth, rhinoceros, bison, and wild horse from the Dogger Bank, proving that the Bank was until recent times dry land. Jukes Brown believes that the Silver Pit (to the south of the Dogger) is the ancient bed of the Rhine, to which the rivers of the east of England were at one time tributary.

Ocean Deeps.

Areas of the ocean where the depths are over 3,000 fathoms are called "deeps" (German, *Graben*). These deeps are variously named. Sir John Murray named them, according to no definite plan, with the name of some hydrographer or exploring vessel. Foreign oceanographers usually name according to their geographical position—*e.g.*, Tonga Deep. The ocean deeps aggregate 9 million square miles—that is, 6·65 per cent. of the ocean floor. The number of recorded deeps is 57, of which 32 occur in the Pacific, 5 in the Indian, and 19 in the Atlantic Ocean. One is partly in the Indian and partly in the Atlantic Ocean.

One additional feature of the oceanic deeps must be mentioned. They are often trough or trench shaped and close to continental land, though some are of irregular outline or basin-shaped. Practically every deep has its corresponding mountain fold, and, in fact, all the deeps lie near and parallel to recent folds in the earth's crust. In some cases the vertical distance from the greatest depth of a deep to the peak of the highest mountain in the associated mountain fold is remarkable. In the deep off Japan soundings of 4,655 fathoms, or 27,930 feet, have been recorded; if this be added to the height of Fusiyama, 12,400 feet, we get a vertical distance of 40,330 feet. Similarly off the west coast of Northern Chili there are

soundings of 4,175 fathoms, or 25,050 feet; to this may be added the height of the neighbouring mountain Llullayucu, 21,654 feet, making a total distance of 46,704 feet.

THE PRINCIPAL OCEAN DEEPS.

Name.	Locality.	Area in Square Miles (Thousands).	Greatest Depth (Fathoms).
Valdivia	S. Atlantic and Indian Oceans	1,136	3,134
Murray	Central N. Pacific	1,033	3,540
Tuscarora or Japan	Off Japan	908	4,655
Wharton or Sunda...	Eastern Indian Ocean	883	3,828
Nares or Porto Rico	Off West Indian Islands	697	4,662
Aldrich or Tonga ...	Central S. Pacific	613	5,022
Swire or Phillipine	N.W. Pacific	550	4,767
Tizard or Romanche	S. Atlantic	468	4,030
Buchanan	E. of S. Atlantic Ridge	298	3,063
Brooke	N.W. Pacific	282	3,429
Moseley	N. Atlantic	279	3,309
Bailey	N.W. Pacific	241	3,432
Jeffrey	Eastern Indian Ocean	228	—
Belknap	Central Pacific	165	3,337
Chun	N. Atlantic	159	3,318
Challenger or Marian	W. Pacific	129	5,269

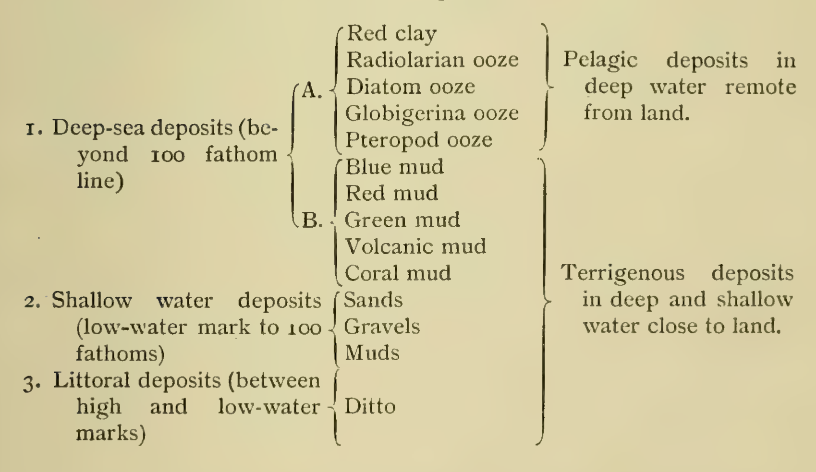
The greatest depth so far recorded is 5,269 fathoms (31,614 feet) in the North Pacific near the island of Guam.

CHAPTER II

Oceanic Deposits and Bottom Fauna

The classical account of oceanic deposits is that by Murray and Renard in the Report of the Scientific Results of the Voyage of H.M.S. *Challenger*, published in 1891. On this report the following synopsis is mainly based, with allowances for the results of more recent investigations. Murray's classification, which was based not only on the material collected by the *Challenger*, but also on the observations of the *Gazelle*, *Blake*, *Albatross*, and other expeditions, is as follows :

Marine Deposits.



1. Deep-sea deposits (beyond 100 fathom line)	A.	Red clay Radiolarian ooze Diatom ooze Globigerina ooze Pteropod ooze	Pelagic deposits in deep water remote from land.
	B.	Blue mud Red mud Green mud Volcanic mud Coral mud	Terrigenous deposits in deep and shallow water close to land.
2. Shallow water deposits (low-water mark to 100 fathoms)		Sands Gravels Muds	
3. Littoral deposits (between high and low-water marks)		Ditto	

Another scheme of classification divides the oceanic deposits into three main groups according to the origin of the constituents of the deposit :

1. *Littoral* (derived from land denudation)	Shore deposits (3 above). Continental shelf deposits (2 above).
2. *Hemipelagic* (partly of land, partly of marine origin)	1 B. above.
3. *Eupelagic* (of marine and cosmic origin)	1 A. above. The red clay and radiolarian ooze being distinguished as abyssal, the remainder as epilophic.

The former classification is followed in this book.

Littoral Deposits.

The littoral deposits (in the narrower sense), as defined by Murray and Renard, include those between high and low water marks. As defined by continental writers, the littoral deposits include those of the continental shelf as well. In the former sense the littoral deposits are estimated to cover 62,500 square miles of the earth's surface. They consist essentially of boulders, gravels, and sands, though mud is by no means unknown in sheltered bays and estuaries. Their nature is determined by the local features of the adjoining land. There is almost an infinite variety of the littoral deposits, from huge boulders resulting from the denudation of cliffs to fine mud.

The seaward limit in the British Isles is often marked by a growth of seaweed known as Laminaria.

The littoral zone is the habitat of a large number and variety of organisms, these naturally varying from the mangrove swamps and coral reefs of the tropics to the shell-fish beds of temperate regions. Generally speaking, the animal life is abundant, the chief groups represented being the Mollusca (cockles, mussels), Crustacea (crabs), Echinoids (sea urchins and starfish), and worms. Some of these organisms are of economic importance, giving rise to extensive "fisheries"—*e.g.*, for mussels, cockles, periwinkles, and clams (in the U.S.A.).

The Shallow-Water Deposits.

These are met with from low-water mark to the 100-fathom line. According to Murray and Renard, they cover about

10 million square miles of the earth's surface. These deposits are also built up entirely of material derived from the land. Their constituent materials are smaller in size than those of the littoral deposit, but larger, as a rule, than deep-sea deposits. Gravels, sands, and coarse material predominate, but mud is by no means uncommon in grooves and depressions, especially in enclosed basins. The mechanical effects of erosion are everywhere recognisable, naturally more marked in the shallower regions. These effects are due to waves, and tides, and currents.

Areas of Oceanic Deposits

(Expressed as percentages).

Littoral and shallow-water deposits		9·1
Deep-sea deposits (Terrigenous)		15·4
Pelagic		
Globigerina ooze	29·2	
Pteropod ooze	·4	
Diatom ooze	6·4	
Red clay	36·1	
Radiolaria ooze	3·4	
		75·5
		100·0

Deep-Sea Deposits.

These are found on the sea bottom beyond the 100-fathom line down to the greatest oceanic depths. They cover considerably more than one-half of the earth's surface and over 90 per cent. of the sea-area (see table above).

Gravels and sands are only met with accidentally in deep-sea deposits, where depths over 100 fathoms are near the land. The chief deposits are muds, clays, and oozes, the last of organic origin. In certain areas the deposits are appreciably affected by the detritus deposited by floating ice. There is in general an absence of the phenomena of erosion. Since sunlight penetrates very little beyond 100 fathoms, it follows that plant remains are scanty except near that limit. Animal life,

for the most part derived from the remains of pelagic (as distinct from demersal) forms, is, however, universally met with, though more abundantly in the shallower areas. The temperature is very low, being below 40° F. over the greater part of the area. The conditions are uniform over very wide areas. Chemical action is characteristic, and results in the formation *in situ* of, amongst other products, glauconite, phosphatic and manganese nodules, and zeolites. The change from one kind of deposit to another is often very gradual, and there is evidence that one deposit may overlie another, though borings from the deep-sea areas are as yet scanty and of only a few inches in depth.

Terrigenous Deposits.

The terrigenous deep-sea (hemipelagic) deposits occupy 15·4 per cent. of the ocean floor. The terrigenous deposits of the littoral and shallow-water zones are really of the same nature as those forming the terrigenous deposits of the deep sea (*i.e.*, beyond the 100-fathom line). These latter are, however, more uniform, homogeneous, fine-grained, and widely distributed, than the former. Of the terrigenous deep-sea deposits in the narrower sense Murray distinguishes three classes—the Blue, Red, and Green Muds. The two other classes included in this group, the Volcanic Mud and Coral Mud, have, as their names indicate, certain special features which render their separate consideration advisable.

Fresh water carries a much larger amount of sediment in suspension than salt water; consequently where a mixture of these waters takes place there is a rapid deposit of sediment on the sea bottom. This was first observed by W. H. Sidell in 1837 in the Mississipi delta,* who noticed that the rate of deposit was greater than that to be expected from a mere decline in the velocity of the current. Since then many experiments have been made on the relative suspension

* See Abbot and Humphreys, Report on the Mississipi, p. 876.

capacity for solids of waters of varying degrees of salinity, notably by the Americans, Hilgard* and Boliver.†

Blue Mud is the commonest deposit met with in the deeper waters surrounding continental land, and in all enclosed or partly enclosed seas more or less cut off from the open ocean. When collected it is blue or slate coloured, with an upper red or brown layer in immediate contact with the water. The blue colour is due to iron sulphide and organic matter. These muds have, as a rule, a small quantity of sulphuretted hydrogen. The reddish tint of the uppermost layer is due to ferric oxide or ferric hydrate; as the deposit accumulates the oxide is transformed into sulphide. When dried the deposit becomes grey or brown, owing to the oxidation of the sulphide of iron. When wet, this mud is plastic and behaves like a true clay, but it is really more earthy than clayey. The percentage of carbonate of lime varies from nil to 35. Blue mud is principally made up of land detritus (quartz being the characteristic mineral), which becomes less abundant with increasing depth, until finally the blue mud passes gradually into one of the types of pelagic deposits.

Blue mud areas afford an important example of the reduction of submarine clay after deposition. Reducing conditions obtain where there is an excess of putrefiable organic matter which cannot be dealt with by the supply of oxygen available. Oxidation of the ferric iron is effected probably by bacterial agency. It is known that bacterial production of ferrous sulphide and free sulphur takes place. It may be that sulphur plays an important part in the formation of blue muds, the final product being a clay in which most of the iron has been reduced to the ferrous state, containing 1 or 2 per cent. of amorphous black organic substances. Murray and Renard give 58 examples of blue mud, of which 12 are from depths less than 500 fathoms, 9 from over 2,500 fathoms.

The average percentage of $CaCO_3$ is 12½, ranging from

* *Amer. Journ. Sci.*, vol. xvii., 1879.

† *Mem. Nat. Acad. Sci.*, Washington, vol. ii., 1883.

the merest trace in 2,650 fathoms to 35 per cent. in 500 fathoms. The pelagic foraminifera make up 7½ per cent. of the $CaCO_3$. The blue muds surround nearly all coasts and fill nearly all enclosed seas—*e.g.*, the Mediterranean and the Arctic. Of all the terrigenous deposits they occupy the greatest space—viz., 14½ million square miles, of which 4 millions are in the Arctic, 3 in the Pacific, 2 in the Atlantic, 1½ in the Indian Ocean.

Since the *Challenger* expedition Weber has collected typical blue mud in the *Siboga*, especially in Banda Sea.

Red Mud is a local variety of blue mud found in the Yellow Sea and off the coast of Brazil, where great rivers bring down sediment from the land. It is characteristic of tropical and subtropical seas into which drain rivers traversing laterite* areas.

The red colour is due to large quantities of ochreous matters, the colouring being due to iron oxide. Red mud is especially characteristic of the South American shelf. It contains no glauconite. The organic matters present, though abundant, are not sufficient to reduce the peroxide of iron to the state of protoxide.

Murray and Renard describe ten samples from the *Challenger* expedition, the percentage of calcium carbonate ranging from 6 to 61, the average being 32. This carbonate of lime is derived from the shells of pelagic foraminifera.

Siliceous organisms such as diatoms and radiolaria are very rare. The mineral particles from the neighbouring land constitute from 10 to 25 per cent. of the whole, the average being 21 per cent.

Green Muds and Sands.—Green mud is a variety of blue mud distinguished by an abundance of grains of glauconite, usually associated with phosphatic concretions. It is found off high coasts with few rivers to pour detritus into the sea—

* Laterite is a cellular, reddish, ferruginous clay found in some tropical countries as the result of subaerial decomposition of rocks.

e.g., the Cape of Good Hope, east coast of Australia, Japan, and the Atlantic coasts of the United States.

Glauconite is a hydrous double silicate of potassium and trivalent iron ($KFeSi_2O_6Aq$). Its chemical origin is still a mystery. It appears to result from a metamorphosis of ferruginous clay, and since it is most often found within the shells of foraminifera, decomposing organic matter probably plays a part in its formation. It is a mineral belonging to the reducing areas of the deep sea.

Glauconite is responsible for the withdrawal of potassium from solution in the sea. All submarine muds and clays contain only a small amount, less than 1 per cent., of potassium. In glauconite areas the fixation of potassium must be considerable, since the purest green sands contain from 7 to 8 per cent. In spite of this the addition of potassium to sea-water probably exceeds its withdrawal, and potassium is slowly accumulating in sea-water.

Glauconite sands are found off the east coast of the United States from Cape Hatteras southward. The collections of the *Tuscarora* show the sands as present off the coast of California at depths of from 100 to 400 fathoms.

Pure glauconite sands such as these are, however, rare, the deposits containing, as a rule, remains of calcareous organisms, mineral particles from the continental rocks, and considerable clay. Blue mud has always more clayey matter than the green muds. Green sands and muds are not found in very deep water, between 100 and 900 fathoms being the rule.

The *Challenger* records contain 22 samples of green mud and 7 of green sand. Carbonate of lime is present from mere traces to 56 per cent., the average being 26 per cent.

Volcanic Muds and Sands occur off those coasts and oceanic islands where volcanic rocks prevail. The volcanic mineral particles are larger in the shallower waters nearer the land, and the deposits are here called volcanic sands. Strictly speaking, volcanic muds are a variety of blue mud. They are light brown, grey, or black in colour, and have an earthy

rather than a clayey nature. In some regions they pass gradually into blue and green muds, in others into coral muds and sands, or with increasing depth into globigerina, pteropod, and diatom oozes, or red clay. There are 38 examples of volcanic muds in the *Challenger* collections, in depths from 260 to 2,800 fathoms, the average being 1,033 fathoms.

The average percentage of carbonate of lime is 20·5.

The volcanic muds and sands are found around all oceanic volcanic islands. They cover an area of about 750,000 square miles.

Coral Muds and Sands are found in the vicinity of coral reefs and islands. They are derived from the débris of coral reefs. In shallow waters sands are formed, but beyond the limits of wave action a mud of triturated particles of calcareous matter is met with.

The predominant feature of the deposit is carbonate of lime, which averages 85 per cent.

Coral muds and sands cover 2,700,000 square miles of the ocean bed. By far the greatest area is in the Pacific (1½ million square miles), the Atlantic coming next with 800,000, and the Indian Ocean last with 400,000 square miles.

Pelagic Deposits and Fauna.

The pelagic deposits (eupelagic of Krümmel) are predominantly composed of the shells of marine organisms. The red clay is, however, an exception to this statement. The remains of pelagic organisms that have fallen from the surface form the chief part of many of these deposits—*e.g.*, the pteropod, globigerina, diatom, and radiolarian oozes. These shells are composed of either carbonate of calcium or silica. In the very deepest areas neither calcareous nor siliceous remains predominate, the basis of the deposit being red clay. This clayey matter is derived from the decomposition of volcanic materials; quartz or other terrigenous particles are either very rare or entirely absent. The physical conditions in these areas are remarkably uniform; the temperature is near

the freezing-point of fresh water, and its range does not exceed 7° F., being constant throughout the year at any one locality.

Sunlight and vegetable organisms are entirely absent. Although most of the groups of marine organisms are present, there is no great wealth either in the number of individuals or species. Many of the species present archaic characters. The inhabitants of the *abyssal plain* are of exceptional interest. About two-thirds of the ocean floor is covered by 2,000 fathoms of water (58·4 per cent. between 2,000 and 3,000 fathoms, and 6·7 over 3,000 fathoms deep), the whole forming a plain over 90½ million square miles in extent, or nearly half the surface of the earth. The amount of trawling and dredging that has taken place over this extensive area is really very slight, and it must not be forgotten that even when there is evidence that the dredge or trawl has fished successfully on the bottom, species of pelagic habit may be captured accidentally while the dredge or trawl is being hauled inboard. Some animals have certainly been captured on the bottom, and these include worms, molluscs, holothurians (sea-cucumbers), starfish, and corals. Fish and crustacea may have been caught at the bottom or at intermediate depths. In some cases it is easy for an expert to say whether a given fish or crustacean has been accidentally taken while the trawl is being hauled in, but in the other cases it is difficult, if not impossible, to say whether a captured fish or crustacean was taken on the bottom or not. Many lists of so-called deep-sea captures contain the names of species which are unquestionably pelagic and not demersal forms. If the strictest tests be applied, then the number of animals—*e.g.*, fish—which are certainly found below the 2,000-fathom line is, according to present knowledge, quite small.

Hjort has summarised (1912) the available information in the case of fish. According to him there are only 35 individuals belonging to 21 species and 6 families of fish which have really been captured at these depths. Even of these he is doubtful as to 12 forms, and he would only regard 23 individuals, 15

belonging to the family Macruridæ and 8 Zoarcidæ, as being certainly captured on the abyssal plain.

This is the total result of all attempts to capture bottom fish beyond the 2,000-fathom line. This scarcity of fish is associated with a scarcity of other forms of life. In the *Challenger* reports large numbers of species of invertebrates are known only from a single locality, and often from one specimen only. The abyssal fish have a wide distribution, both horizontal—*i.e.*, they are found at places wide apart in the different oceans—and vertical—*i.e.*, they occur on the continental slopes as well as on the abyssal plain.

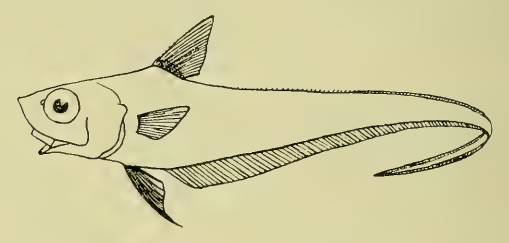


FIG. 4.—ABYSSAL FISH (MACRURUS).



FIG. 4A.—ABYSSAL FISH (LYCODES).

Sir John Murray has summarised the results of the deep-sea trawling and dredging of the *Challenger* expedition. At 25 stations where the depth exceeded 2,500 fathoms 600 individual animals were captured; this gives 24 individuals per haul. Many of these, however, are undoubtedly pelagic—certainly most of the crustacea and some of the fish.

Some of the other organisms were very small—*e.g.*, hydrozoa and bryozoa. It is certain that animal life is very poorly developed on the abyssal plain.

The Norwegian fisheries' investigation steamer *Michael Sars* has made three successful hauls at depths of over 2,500

fathoms with an otter trawl much larger and more effective than any of the gear used on the *Challenger*. This net had a head-rope 50 feet in length, and the opening of the net may be considered to be not much less than this. At 2,800 fathoms it took over five and a half hours to shoot and over six hours to haul the trawl. Unfortunately, after three successful hauls from the abyssal plain the trawl was lost. The results of these three hauls confirmed the *Challenger* results, and show that fish and invertebrate life is very scanty at depths exceeding 2,000 fathoms. The distance to which shoals of edible demersal fish extend downwards from the continental slope is a question of considerable practical importance, since the great trawl fisheries of Northern Europe are only limited by the ground on which fish of economic value are found in sufficiently large quantities to make trawling a commercial success. If the boundary of the abyssal plain be fixed at 2,000 fathoms, the area between 2,000 and 1,500 fathoms may be considered as a transitional zone between the abyssal plain and the continental shelf. The area between the 1,000 and 2,000 fathom line comprises 19·3 per cent. of the ocean floor, so it is a by no means negligible area in point of size, seeing that practically the whole of the present deep-sea trawling is carried out on an area shallower than 100 fathoms—*i.e.*, 7 per cent. of the sea bottom.

Between 1,500 and 2,000 fathoms the *Challenger* made 25 hauls, the *Michael Sars* 3. Here the fish and invertebrates are much more abundant, but still in nothing like sufficient numbers to pay commercial trawlers.

Between 1,000 and 500 fathoms, 3 per cent. of the ocean floor, the number of fish, though relatively more abundant, still only averages about 90 per haul.

From 100 to 500 fathoms, 5·6 of the ocean floor, edible fish are certainly present in some localities in sufficient abundance to pay commercial trawlers, even when the difficulties and expense of trawling at these great depths are taken into consideration. At depths of 500 fathoms the *Michael Sars*

obtained 300 fish in one haul. The upper limit of the abyssal species appears to be somewhere between 500 and 450 fathoms.

In from 300 to 350 fathoms we get fish—*e.g.*, the hake—which probably, though not certainly, are present in sufficient numbers to render commercial trawling a success. It is almost certain, however, that this is the extreme limit for commercial fishing.

It may be taken for granted that one of the main limiting factors in the bathymetrical distribution of fish is the food question. According to Murray, the limit of wave action in the open ocean coincides with the mud line, and the average depth at which mud begins to be deposited is 100 fathoms. For a few hundred fathoms beyond the mud line animal life, especially crustacea, is exceedingly abundant, and Murray terms this area the "great feeding-ground" of the ocean. The surface layers of the organic deposits in moderate depths (the organic oozes) yield an abundant food for the Benthos. With rapidly increasing depths into the red clay the quantity of food diminishes, and the bottom fauna is consequently less abundant. The *Challenger* summary shows that animal life was found most abundantly on the terrigenous deposits, though the globigerina ooze is also very rich in organisms. While the fishes of the continental shelf live on terrigenous deposits, the *Michael Sars* experiments prove that in the Eastern Atlantic most of the fauna live on the globigerina ooze. Although it is true that it is not only the terrigenous deposits which maintain an abundant bottom fauna—still, fish of edible species are confined to the continental shelf and slope and its immediate vicinity.

The increasing demand for demersal fish by the countries of Northern Europe will unquestionably lead to an effort to extend the trawling activities of British and other fishermen. Since the grounds on the continental European shelf have been fairly extensively fished already, it follows that the investigation of new areas will sooner or later prove necessary. The bottom water of the Norwegian Sea (the area bounded

roughly by Norway, the Shetlands, Iceland, Greenland, and Spitsbergen) is quite cold, most of it below 0° C., the abyssal plain itself having water of temperature below − 1° C. So far as our information goes, the valuable trawl fish, Gadidæ (cod family) and Pleuronectidæ (plaice family), are absent from this cold water. A few fish, of relatively inferior edible qualities, are alone captured in the deeper waters. The coastal banks off Greenland, Jan Mayen, and Spitsbergen, which, unlike those off Iceland and in Barents Sea, have not yet been explored by commercial trawlers, are frequented by certain cold-water species about whose distribution and abundance more information is required. The only Gadoid at all abundant is the polar cod (*Gadus saida*). Other species that *may* be taken are the Norway haddock (*Sebastes norwegicus*), a species of gurnard, and the saithe. There can, however, be no doubt that the distribution of certain species of fish is closely connected with the presence of water of a certain temperature, with its characteristic invertebrate fauna. For instance, the southern limit of the characteristic northern species coincides with the isotherm of 10° C. At a depth of 50 fathoms this line runs across the Atlantic from the border of the northern and middle States of North America to the north-west of Ireland.

On the west side of the Atlantic the isotherms between 12° C. and 4° C. are at 50 fathoms closely squeezed together, whereas on the east side they are widely separated. West of the British Isles the influence of the Gulf Stream plays an important part, so that here such northern species as the cod, saithe, tusk, and halibut, are not captured.

The westward limit of our trawlers' activity is limited by the line to which the fauna of the continental shelf extends, and this may be taken to be, for practical purposes, 300 fathoms, up to which commercial trawling is successful, the fish found at the greatest depths here being ling, hake, and bream. The average temperature at 300 fathoms west of Ireland is approximately 10° C. The distribution of the

various edible species on the continental shelf itself may be referred to elsewhere.*

The northern limit of possibility of commercial trawling is uncertain. Already, as stated above, the south coast of Iceland and the banks off the Murman Coast (Barents Sea) are fished by British trawlers.

From 50 down to 300 fathoms on the northern edge of the North Sea plateau saithe, ling, tusk, and halibut are captured. All along the edge of the continental shelf from Spitsbergen and Bear Island along the coasts of Norway, the North Sea plateau, the Faroes, and the Faroe Iceland ridge, the following are taken: Norway haddock, blue ling, black halibut, and other species.

Probably edible species may be captured in depths up to 300 fathoms in the Norwegian Sea. Below that depth the water is certainly too cold to support edible fish and their food in quantity. Even above that depth there may be large areas without abundance of fish life.

Large halibut are known to occur off the west of Bear Island, round the North Sea plateau, the Faroes, and on to Iceland.

Hjort divides the northern pelagic communities into three groups—(1) the Arctic, (2) the Boreal, and (3) the temperate Atlantic.

In the Norwegian Sea the Arctic water is found in the Greenland Sea in the west, in Spitsbergen in the north, and even close to the banks of Norway and the North Sea, and this water excludes fish of the second and third groups above.

Since the first group, the Arctic, comprises only a few forms, of which the Polar cod and the capelan (*Mallotus villosus*) are alone present in quantity, it may be assumed that the prospect of any northern extension of the present commercial trawling areas is extremely unlikely.

* See "The Sea Fisheries," by J. T. Jenkins. London: Constable, 1920.

The Pelagic Deposits are divided into five main types :

1. *Pteropod Ooze* is found in the shallower waters, far from continental land, on tropical and subtropical ridges, and comes especially within the coral reef regions where warm water with small annual variation is found at the surface. It consists mainly of shells of pteropods and heteropods. Although these mollusca are found practically everywhere in the surface waters of tropical and subtropical regions, their dead shells are absent in the deeper deposits. A few traces are met with down as low as 2,000 fathoms. The *Challenger* lists comprise thirteen samples, only one of which is from over 1,500 fathoms deep.

Pteropod ooze was only found by the *Challenger* in the Atlantic, where it occurs near the Azores, the Antilles, west of the Canaries, and on the South Atlantic median ridge between Ascension and Tristan da Cunha. This ooze has also been found by other expeditions in the Indian (by the *Valdivia*) and Pacific Oceans.

The total area is small, not exceeding 0·4 per cent. of the ocean floor. The percentage of carbonate of lime is, of course, high, averaging 80 per cent.

2. *Globigerina Ooze* forms 29·2 per cent. of the ocean floor. The average depth of the ocean is about 2,000 fathoms, and this ooze is the most widely distributed on these average depths. It is made up largely of the dead shells of surface foraminifera, the genus globigerina predominating.

Globigerina ooze was originally obtained by the cable steamers in the North Atlantic, where it was first collected by Lieutenant Berryman of the U.S. Navy, and described by Ehrenberg and Bailey in 1853. These foraminifera occur also in other deposits, the term "globigerina ooze" being restricted to those which contain over 30 per cent. of carbonate of lime, mainly made up of the dead shells of foraminifera. The majority of the surface living foraminifera, from whose shells this deposit is mainly derived, live in warm tropical waters.

The colour of the ooze is white, yellowish, or greyish,

depending on the nature of the inorganic substances mixed up with the foraminifera. The prevailing colour is milky-white or rose-coloured far from land, and dirty white, blue, or grey, near land. In the *Challenger* lists there are 118 samples of this ooze, the bulk (84) being between 1,500 and 2,500 fathoms. There are only 5 samples below 1,000 fathoms and 16 from over 2,500 fathoms.

The carbonate of lime varies from 30 per cent. in 2,575 fathoms to 97 per cent. in 425 fathoms. The average is 64½ per cent. The amount of carbonate of lime diminishes as the depth increases. Although the organic substance in globigerina ooze is not large, this deposit does yield abundance of food for the Benthos.

Such creatures as echinoderms and annelids are nourished by the ooze which they pass through their alimentary canals.

The average composition of the *Challenger* globigerina ooze is:

	Per Cent.
$CaCO_3$	64·47
Siliceous organisms	1·64
Minerals	3·33
Fine washings	30·56
	100·00

The siliceous organisms are mainly radiolaria; then follow sponge spicules and diatom frustules.

Of minerals which have been formed *in situ*, the globigerina ooze contains glauconite, phosphate concretions, and manganese nodules. The glauconite (see under Green Sands above), though not abundant, is widely distributed, and occurs as a nucleus of what was originally an enveloping calcareous chamber.

The phosphatic concretions are rare in globigerina ooze. They are of very localised occurrence, and are, in the last resort, of biological origin. They vary greatly in size and form, and are made up of heterogenous fragments (grains of glauconite or other minerals or remains of organisms) cemented

by phosphatic material. When the cemented particles are purely mineral, the phosphatic material acts simply as a cement, but when there are remains of calcareous organisms in the concretions the calcium carbonate of the shell is pseudomorphosed into calcium phosphate.

Manganese nodules are not especially abundant in globigerina ooze.

The oxides of iron and manganese are widely distributed in marine deposits. They occur in minute grains, and act as colouring matter in all deep-sea clays. The commonest form is more or less rounded nodules of varying size, so that in one area they look like marbles, in another like potatoes or cricket-balls. Generally the nodules are concretions formed round a nucleus which may be a shark's tooth or whale's ear-bone, or a piece of pumice or fragment of volcanic glass.

The manganese of the nodules is chiefly derived from the decomposition of the more basic volcanic rocks and minerals with which the nodules are nearly always associated in deep-sea deposits. The manganese and iron of these rocks and minerals are at first transformed into carbonates and then into oxides, which, on depositing from solution in the watery ooze, take a concretionary form around various nuclei.

Among the other foreign bodies present in globigerina ooze note must be made of glaciated stones. These glaciated fragments were found by the *Challenger* west of the Azores (to 35° N. Lat.). If the position of these fragments be compared with a map showing the distribution of icebergs, it will be seen that they are all within, or just beyond, the limits of the iceberg regions. They are therefore due to floating ice.

Globigerina ooze has a very wide distribution on the ocean floor. Its total area is over 49½ million square miles, coming second only to the red clay. Its maximum development is in the Atlantic (22½ million square miles), occupying by far the larger portion of the sea floor of this ocean from the Arctic Circle to 60° S. Lat.

In the Indian Ocean it occupies about 12¼ million square

miles, covering nearly the whole of the western portion of the basin. In the Pacific the area is over 14¾ million square miles.

3. *Diatom Ooze* is a siliceous sediment composed mainly of the shells of plants (diatoms). It is found in high latitudes in both hemispheres, and originates in the phytoplankton. The name was introduced by Murray in his *Challenger* report, and

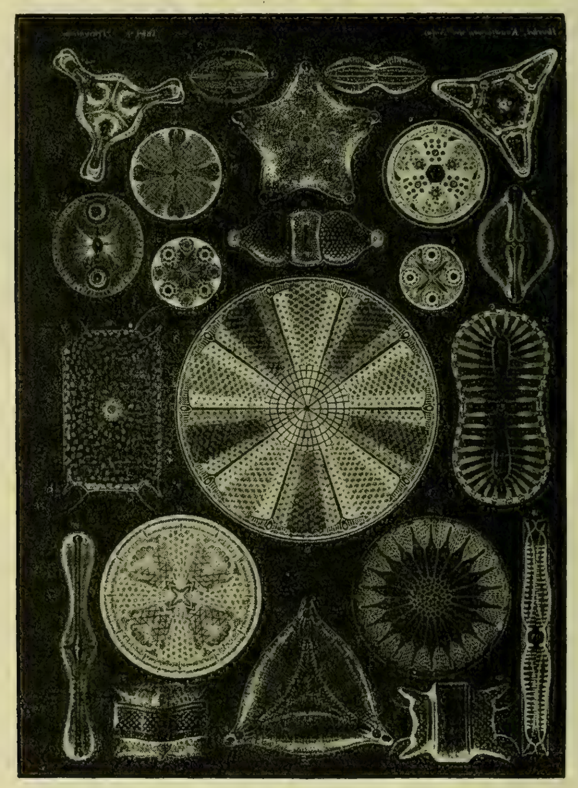


FIG. 5.—BOTTOM AND PELAGIC DIATOMS.

applied to a deposit which, when wet, has a yellowish straw or cream colour; when dry, nearly pure white, resembling flour. The surface layers are thin and watery, the deeper layers laminated. Near land it takes on a bluish tint. The calcium carbonate percentage is low, ranging from 3 to 30 per cent.

Diatom ooze forms a wide zone round the South Polar regions, lying for the most part between the Antarctic Circle and 40° S. Lat., where it covers over 10¾ million square miles. There is also a girdle in the North Pacific extending to 40,000 square miles.

The last two sediments, the (4) *Red Clay* and (5) *Radiolarian Ooze*, are sometimes called the abyssal deposits, since they occupy the greatest depths and widest areas of the ocean floor. The radiolarian ooze may, in fact, be regarded as a local variety of the red clay.

Radiolarian ooze is characteristic of deep water in the tropical regions of the Pacific and Indian Oceans. While resembling the red clay in many respects, it differs in containing a large number of siliceous remains, the shells of radiolaria for the most part, though sponge spicules and diatoms are present. Nine samples were collected by the *Challenger* expedition at an average depth of 2,894 fathoms, which is deeper than the red clay average, 2,730 fathoms.

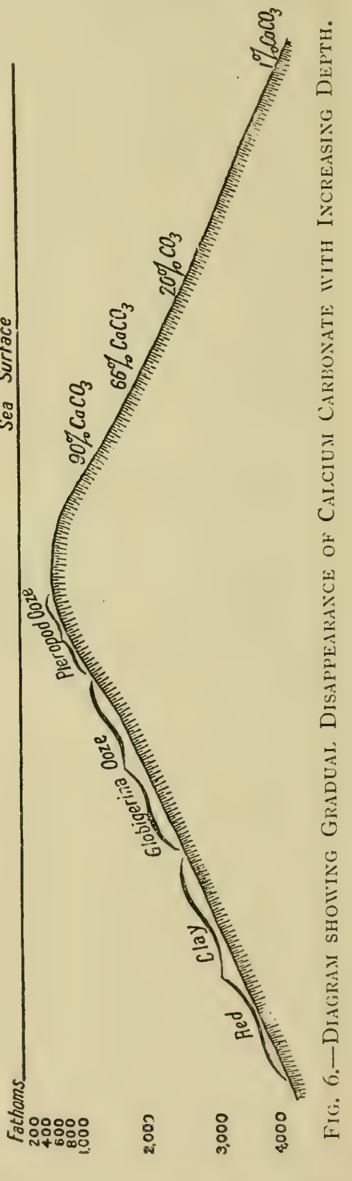


FIG. 6.—DIAGRAM SHOWING GRADUAL DISAPPEARANCE OF CALCIUM CARBONATE WITH INCREASING DEPTH.

The amount of carbonate of lime ranges from a trace in five cases to 20 per cent, as a maximum, the average being

4 per cent. Calcium carbonate disappears with increase of depth.

Down to 1,000 fathoms nearly every shell of pelagic (surface) organisms is represented in the deposit, even the smallest and most delicate. At 1,500 fathoms the thinnest and smallest shells disappear, and pteropod ooze passes gradually into globigerina ooze.

At 2,000 fathoms the pteropods have disappeared entirely, and some of the more delicate foraminifera as well. At 2,500 fathoms the larger and thicker foraminifera still remain, and the deposit becomes a red clay with some carbonate of lime. At 4,000 fathoms hardly a trace of these shells can be found, and chemical analysis shows barely 1 per cent. calcium carbonate.

And this although the living organisms at the surface are as abundant over the red clay areas as over the pteropod ooze areas. It is at about 2,500 fathoms that the percentage of calcium carbonate in the deposits falls off very rapidly. According to Murray, it would take from three to six days for shells to reach a depth of 2,500 fathoms. Calcium undergoes extensive circulation between the dissolved and undissolved states in the ocean. When calcareous fragments fall on a clay or mud bottom they fall into water which can take up lime, and are dissolved. When they fall in calcareous deposits, such as pteropod ooze, they fall into water layers which can dissolve no more lime. In areas over globigerina and pteropod oozes lime is being withdrawn from the ocean. Over red clay areas lime is returned to the ocean. Probably a balance is struck, though, on the whole, lime at the present time appears to be accumulating towards the Equator.

Red Clay is characteristic of the greatest depths on the ocean floor. It is the most widely distributed of deep-sea deposits. First discovered by the *Challenger* in depths exceeding 2,400 fathoms between Tenerife and the West Indies, it was first thought to be the ultimate sediment produced by disintegration of the land. Wyville-Thomson, the leader of the *Challenger*

expedition, thought it was primarily of organic origin, being essentially the insoluble residue of the calcareous organisms which form the globigerina ooze. He further suggested that clay, which is generally regarded as essentially the product of the disintegration of older rocks, may in certain cases be of organic origin like chalk. Murray believes that the clayey matter in marine deposits far from land is principally derived from the decomposition of aluminous silicates and rocks spread over the ocean basins by subaerial and submarine eruptions.

The basis of red clay is hydrated silicate of alumina associated with secondary products, such as manganese-iron nodules and phillipsite.

There are seventy samples in the *Challenger* collection from an average depth of 2,730 fathoms. The colour of the deposit varies greatly, but red is the prevailing tint. In the North Atlantic brick-red, and in the South Pacific and Indian Oceans dark chocolate, predominates. Calcareous matter may be entirely absent; in lesser depths it may be 30 per cent. when the deposit passes gradually into globigerina ooze. Red clay is soft, plastic, and greasy. It can be moulded between the fingers like dough.

The rate of accumulation of red clay is evidently a minimum, since the calcareous shells falling from the surface are removed either before or shortly after they reach the bottom. In the dredge are found ear-bones of whales and teeth of sharks (many of extinct species), and these are impregnated and coated with peroxides of manganese and iron. There are also present minute chondritic and metallic spherules which are supposed to have fallen from interstellar space.

The average composition of red clay is:

$CaCO_3$	6·70
Siliceous organisms	2·39
Minerals	5·56
Fine washings	85·35
	100·00

The fine washings consist essentially of hydrated silicate of alumina.

Red clay has not been found in less depths than 2,200 fathoms. Radioactive substances are found more abundantly in red clay than in any other marine deposit, or in any continental rocks.

Red clay is the most widely distributed oceanic deposit. It occupies the deepest portions of the great oceans, except in Polar regions, extending from 50° N. to 50° S. in the Pacific, where it is the main deposit, and between 40° N. and 40° S. in the Atlantic.

Stratification in Marine Deposits.

Samples of marine deposits are only known to a depth of 1 or 2 feet, so that our knowledge of their stratification is slight. The tubes attached to sounding leads do not bring up portions of the bottom deposit of more than a foot in depth, except in rare instances. In these samples there is sometimes clear evidence of stratification. Phillipi, who examined the bottom samples collected by the German South Polar investigation steamer *Gauss*, believes that stratification is the rule in bottom deposits.

Generally speaking, there is a difference in colour and chemical composition between different layers of the same deposit—*e.g.*, blue mud is stiff and blue in colour in its lower portion, thinner and reddish-brown in its upper layers. This is probably due to the ferric oxide or ferric hydrate changing into the sulphide or ferrous oxide in the deeper layers. There are examples of—

(1) Globigerina ooze above red clay, found by the *Challenger* expedition in the South Pacific, pointing to an elevation of the ocean floor.

(2) Red clay above globigerina ooze, found by the *Challenger* also in the South Pacific, pointing to a subsidence of the ocean floor.

(3) Globigerina ooze over blue mud.

(4) Globigerina ooze over diatom ooze; and

(5) Diatom ooze over blue mud.

On the whole the evidence is in favour of a subsidence of areas of the ocean floor.

A final point for consideration is the resemblance between

Oceanic Deposits and Geographical Sediments.

Comparisons have been made between certain geological sedimentary deposits and the various types of marine sediments. All oceanographers agree that it is only the littoral and terrigenous deposits which are comparable to geological sediments of all geological ages. The true deep-sea or eupelagic deposits of marine and cosmic origin are generally considered to be unrepresented in the geological strata. The detailed consideration of these comparisons will be found in textbooks of geology. There are, of course, numerous sedimentary strata which have been unquestionably formed by deposition in marine areas—for instance, the Jurassic strata. But these were not deposited or formed in abyssal regions. The only modern sediment which can be compared with a deep-sea deposit is the chalk. The comparison was made by Huxley in 1858, who stated the globigerina ooze to be a modern chalk. A detailed comparison, however, does not support this view; for instance, the chief genera of the foraminifera found in the chalk are not pelagic, but bottom-living shallow-water forms. The most abundant foraminifer of the chalk, *Textularia globulosa,* is found in the Dee estuary near Chester.

The scarcity, or, according to some authorities, the absence, of abyssal or deep-sea deposits in the sedimentary continental rocks has lead to a theory of the

Permanence of the Oceans.

According to this theory the ocean areas have been permanent from remote geological epochs. The consideration of the various theories—and views from one extreme to the

other have been put forward from time to time—is beyond the scope of this work. Really we know very little of the older sedimentary rocks of extra-European localities, and consequently until these have been more thoroughly investigated and submitted to microscopical examination it is hardly possible to arrive at a definite opinion. The chief points put forward in favour of the theory of the permanence of the great oceanic areas may be summarised as follows :

1. The relative distribution of land and water is against any great change. For any new large mass of land to rise out of the ocean-bed would mean a general submergence, since the volume of the oceanic water greatly exceeds that of the land above sea-level (p. 16).

2. The contours of the ocean-bed show great uniformity of level (p. 17). There is no evidence of geological faults or of subaerial denudation.

"The compression which has caused the thickening, accompanied by corrugation, such as characterises most elevated tracts, is a continental phenomenon and has no analogue beneath the ocean."

3. All continents and continental islands present the same range of geological formations, and such formations are indicative of the near presence of land.

4. There is no true abyssal deposit represented in the geological strata. The chalk is not really a representative of the globigerina ooze.

5. According to Dana, the great oceanic depressions are regions of the maximum radial contraction of the earth, and therefore permanent.

Probably oceanic depths of 2,000 fathoms and over are of great antiquity. For a full account of speculations on this subject the works of Suess, Dana, and Osmund Fisher should be consulted.

CHAPTER III

The Temperature of the Sea.

The accurate determination of the temperature of the sea, not only at the surface, but at varying depths, is one of the chief concerns of oceanographers.

A combination of readings of temperature and salinity enables us to determine the movements of large masses of ocean water and in many instances to determine the extent, distribution, and boundaries of ocean currents.

Observation of surface temperatures is an easy matter, since it is only necessary to haul in a bucket of water and read the temperature rapidly but accurately with a reliable thermometer. Of course, even here certain elementary precautions are necessary.

For readings at intermediate depths special apparatus is necessary. The Pettersson-Nansen water-bottle (see p. 103) collects and insulates water samples from any required depth, and within limits gives an accurate reading of the temperature of the water samples.

In the *Challenger* expedition a maximum and minimum thermometer of the Miller-Casella type was used. At the top of the instrument there are two glass bulbs connected by a bent tube, the left-hand bulb being filled with creosote, the capillary tube containing mercury, the right-hand bulb having a vacuum except for a little creosote.

When the thermometer is heated the creosote in the left bulb expands and pushes the mercury through the tube, and with it a small index which sticks at the place where the mercury leaves it. When the thermometer cools the creosote contracts, and the creosote vapours on the right drive the

mercury back into the left-hand branch, where there is another index-pin.

In this way the maximum and minimum temperatures are registered. Quite good records were obtained with this thermometer.

The best modern deep-sea thermometer is of the reversing type. Of these there are several varieties, those of Negretti-Zambra, Knudsen, Chabaud, and Richter being the chief. All are similar in principle.

In the reversing thermometer there is a narrowing of the tube just above the bulb. The mercury rises and falls in the tube above the narrow portion according to the temperature. When the thermometer has been lowered to the required depth it is reversed by means of a messenger sent down the wire. This causes the mercury to break off at the narrow point, the column of mercury above this point sinking down the tube, where it is now isolated from the mercury in the bulb. To enable the thermometer to withstand the strong pressure at great oceanic depths it is surrounded with a strong glass tube with mercury enclosed around the bulb to act as a rapid conductor of heat.

The severed column lengthens or shortens according to the change in temperature which occurs in hauling the instrument inboard. This change is calculated if the temperature at the time of reading off is known, and consequently it is now customary to enclose a small thermometer inside the strong glass tube, the reading of which gives the data for the correction.

It is now possible with the best types of reversing thermometers to determine the temperature of sea-water to $\frac{1}{100}$ degree Centigrade.

Sources of Heat in the Sea.

There are two possible sources of heat for oceanic water—

1. The inner heat of the earth.
2. The sun's rays.

According to Geikie, the temperature of the earth increases one degree Fahrenheit for every 64 feet of descent. An increase of temperature in the bottom layers of oceanic water as a result of the internal heat of the earth has long been suspected. In 1840 Aimé looked for it, but at that time the thermometers in use were not sufficiently accurate. More recently indications of a rise of temperature towards the bottom have been observed, but since the increase in pressure and the internal heat of the earth would both tend to increase the temperature of the bottom layers of water, it is impossible to say at present how much is due to each cause separately.

Certainly the increase in pressure causes the bottom-water temperatures to be higher than they otherwise would be. The inner heat of the earth passes into the lower layers of water by convection and probably increases the temperature there to a small amount, an amount which has not yet been accurately ascertained.

The second source of heat—the sun's rays—is by far the more important.

Occasionally the surface layers may be heated by contact with warm air, but as a rule the temperature of the sea is higher than that of the air above it.

The sun's rays penetrate the water, the dark heat rays are absorbed near the surface, while the light rays, which also contain some heat, penetrate to a depth of several hundred metres (p. 76) before disappearing altogether.

The sun's rays are strongest in the tropics, diminishing to the north and south.

There is a small daily variation in the temperature of the surface layer of water in the ocean. The average variation is

0·5° C., the maximum temperature being reached between 1 and 2.30 p.m., the minimum between 5 and 8 a.m.

At night the sea is appreciably warmer than the air above it; in the daytime the temperature of the air slightly exceeds that of the sea, but as a general rule the temperature of the surface of the sea is appreciably higher than the air above it.

The conduction of heat plays a minor part in the thermal condition of the sea. According to Wegemann, if a volume of sea-water 5,000 metres deep with a temperature of 0° C. be considered with a source of heat at the surface of 30° C., then after 100 years there would be no increase of temperature at 100 metres deep, after 1,000 years there would be no increase at 300 metres, but at 100 metres an increase of 7·3° C. would be registered, and at 200 metres 0·6° C.

Heat conveyed to the upper layers by the sun's rays is therefore only transmitted to lower layers by movements of the water such as convection currents, or through changes in specific gravity. In the latter case the surface layers are rendered heavier by evaporation in the daytime, and at night this disturbance of specific gravity is corrected by water movements, this leading to the transmission of heat to lower layers.

The Discontinuity Layer.

Where there is a marked difference of temperature in a narrow range of depth we speak of a discontinuity layer (American term, thermocline). This layer is more marked in fresh-water lakes than in the open sea, since in the former there is less disturbance due to waves and currents. In many mid-European lakes there is at depths of from 11 to 13 metres a difference of 2° to 3° C. in a 20-centimetre layer. A sharp discontinuity layer only occurs in confined seas such as the Baltic, where Ekman found near Bornholm at 18 metres a temperature of 14° C., but at 20 metres 8° C. only, although the water in both cases was of the same salinity.

The discontinuity layer is generally a boundary between

two different assemblies of organisms—*e.g.*, fish of a given species are known to frequent exclusively water of a given temperature, or, more accurately, water with a given range of temperature.

Temperatures at the Sea Surface.

Lines joining places in the ocean with identical temperature are called isotherms. The first chart showing isotherms was published by Maury in 1852. The surface temperature varies from an annual average of 27·4° C. to −1·7° C., the warmest water being in 5° N. Lat., the coldest from 80° N. to the Pole and 75° to 80° S. Lat. Generally speaking, the temperature is influenced mainly by the ocean currents, and this is especially noticeable in the tropics.

In high southerly latitudes there is a parallelism between the isothermal lines and the degrees of latitude.

More than half the surface of the sea has an annual average temperature exceeding 20° C. (68° F.). The percentages of the great oceans which have this or higher temperature are—Atlantic 50·1, Indian 51·7, and Pacific 58·4.

Krümmel estimates the average surface temperature in the Northern Hemisphere to be 19·20, in the Southern 15·97; the air temperature averages for the Northern Hemisphere 15·1°, for the Southern 13·6° C.

Of the three great oceans, the Pacific has the warmest surface water, with an average of 19·10° C., the Indian being 17·03, and the Atlantic, the coldest, 16·91° C.

Practically three-fifths of the Pacific Ocean lies between 30° N. and 30° S. Lat., whereas less than half of the Atlantic is so situated.

The coldest surface temperature hitherto recorded is −3·3° C. off New Scotland, the highest, in the open ocean in the West Pacific, 32·2° C. The highest marine temperature is not, as is usually given, the Red Sea (34·4° C.), but the north end of the Persian Gulf, with 35·6° C. (96° F.). The annual variation of temperature in British waters varies from 10° to

12° C. in the Channel to 13° to 14° C. in the southern North Sea. The greatest known variation is in Japanese waters off Yezo, where the annual range is from −2·8° to 28·3° C.—*i.e.*, a variation of 31·1° C. Annual variations in temperature are perceptible to a depth of 150 fathoms.

It is interesting to compare the decrease in temperature with the depth with the decrease at the surface as we pass from Equator to Pole, and this has been done for the North Atlantic:

Zone	0–10°	10–20°	20–30°	30–40°	40–50°	50–60°	60–70°
Temp. ° C. ...	26·83	25·60	23·90	20·30	12·94	8·94	4·26

At 7½° N. the German Antarctic Expedition found in July, 1911, the following temperatures in the Atlantic:

Depth in metres ...	0	100	200	400	800	1,000
Temp. ° C.	26·86	18·57	10·71	7·70	5·13	4·81

At 100 metres the temperature is similar to that in 40° N.; at 200 metres to that in 50° N.; and from 700 to 800 metres to 60° N.

When the water has the same temperature from the surface to the bottom it is said to be homothermous; when there are differences in temperature it is heterothermous.

When the upper layers are warmer and the lower colder it is anothermous; when the upper layers are colder and the lower warmer, the term katathermous is employed.

When the upper layer is warm and the temperature sinks and then rises again in the lowest layers, the term dichothermous is used; when the middle layer is warmer than either the lower or upper, the water is said to be mesothermous.

Although the surface temperatures of the ocean are higher on the average than one would expect, the temperature of the mass of water is low, since the great bulk of the oceanic water—*i.e.*, practically all below 150 fathoms—is not much influenced by the sun's rays. Attempts have been made to calculate the average temperatures of the main oceans at various depths—*i.e.*, at 100, 200, up to 3,000 and 4,000 metres, and from the

estimates thus arrived at an average temperature for the whole mass of the oceanic water of the three great oceans. The averages given by Krümmel are—

Atlantic.	Indian.	Pacific.	Whole Oceans.
4·02° C.	3·82° C.	3·73° C.	3·83° C.

The temperature of the great mass of oceanic water, approximately 38·8° F., is thus low, and shows that the oceans are in the main extremely cold. The main source of organic material in the sea is fortunately met with in cold-water areas. At the same time it must not be forgotten that the upper layers in which the plankton is produced are by far the warmest, and there is a general tendency for warm surface currents to flow from the Equator to the Poles. Of these currents the "Gulf Stream" is the leading example.

This Gulf Stream varies in strength from year to year, and according to many oceanographers, such as Pettersson, there is a direct connection between the thermal conditions of the Gulf Stream in North European waters and the climate of the adjacent countries, and possibly also in the migration of certain fish of economic importance, such as herring (p. 60).

A detailed consideration of the distribution of temperature, both horizontal and vertical, in the various oceans and seas of the globe is beyond the scope of this work.

That, however, it is not a question of purely theoretical interest a few instances will prove.

Most fish of economic importance are found in waters with a certain range of temperature, and in waters above or below certain ranges no fish of commercial value are met with (see p. 35).

In depths of 100 metres (54·6 fathoms) the temperatures correspond to and change with the surface temperatures as a general rule. At 200 metres (109 fathoms) there is a perceptible general lowering of the temperature. At 400 metres (218 fathoms) there are still wide areas in the tropics where the temperature is 10° C. (50° F.) or over, and the influence of

oceanic currents is still very noticeable; and the same general distribution of temperature rules in 600 metres depths (328 fathoms). At a little over 1,000 fathoms (2,000 metres) there is a marked uniformity of temperature, between 2° and 3° C., this being the case in the whole of the Pacific, South Indian, and South-West Atlantic Oceans. At 2,000 fathoms the average temperature is about 1·6° C.

Genuine deep-sea fish such as Macrurus have a wide geographical distribution; nevertheless, this genus is confined to water between 1° and 3° C.

In the North Atlantic warm water extends down to much greater depths on the east side (off Ireland) than on the west side (off the North American coast). From 500 to 800 fathoms it is much warmer on the east side, whereas from 1,000 to 2,000 fathoms the temperatures are similar on both sides.

On the continental *slope* on the east side of the Atlantic from the Faroes to the south of the Canaries the thermometrical conditions are much the same. Thus at 500 fathoms the temperature is 7° C. south of the Faroes and 8° C. south of the Canaries. On the west side at this depth the temperature is only 4° C. Commercial trawling has not yet been carried on at this depth, and from the results of experimental trawling by scientific vessels it does not appear that edible fish are likely to be present in paying quantities.

The Norwegian Sea has an extensive area with depths above 1,000 fathoms inhabited by cold-water fish of little or no commercial value. Below 350 to 400 fathoms the water is extremely cold, mostly below 0° C.

The International Hydrographic Investigations.

A very large number of temperature and other physical observations on the seas of North-Western Europe have recently been made under the auspices of the International Council for the exploration of the sea from a fishery standpoint. These records extend far out into the Atlantic and

Arctic, and the results so far obtained are briefly referred to in the various sections of the book which follow. A brief digression is necessary here in order to explain the constitution and objects of the International Fishery Council, as it is frequently called.

In July, 1899, the Swedish Government invited the governments of the countries interested in the fisheries of the North Sea to join in a scheme for the joint investigation of that and neighbouring seas. Eventually nine countries engaged in a scheme of research—*e.g.*, Britain, Belgium, Denmark, Germany, Finland, Holland, Norway, Russia, and Sweden. Each country had its own staff of scientists, its own exploring vessels and laboratories, and in addition there was a central laboratory set up at Christiania and a central office at Copenhagen, in order that the researches might be properly co-ordinated. This work went on until the outbreak of the war in 1914, when the work at sea came to an end, and in most of the belligerent countries even the work at the shore laboratories was largely curtailed, if not entirely suspended. Each country had allocated to it a certain area of sea for detailed investigation; the appended chart (Fig. 7) shows these areas.

The part of the International Fishery investigations with which we are most concerned is the hydrographic work, which deals with physical investigations on the constitution and movements of the water in the seas of Northern Europe. The area investigated includes not only the continental shelf on which the British Isles stand, but also the deep-water areas separated by the Wyville-Thomson ridge, which joins the Faroes to the British submarine plateau. This ridge extends on past the Faroes to Iceland and Greenland, and it separates two deep-water basins, one in the Arctic, the other in the Atlantic, from one another. Not only is the continental shelf an important fishing-ground, but the ridge and its continuations, or at any rate the banks on them, are potential fishing-grounds. Further information was therefore desired of the physical conditions, not only on the ridge itself, but of the

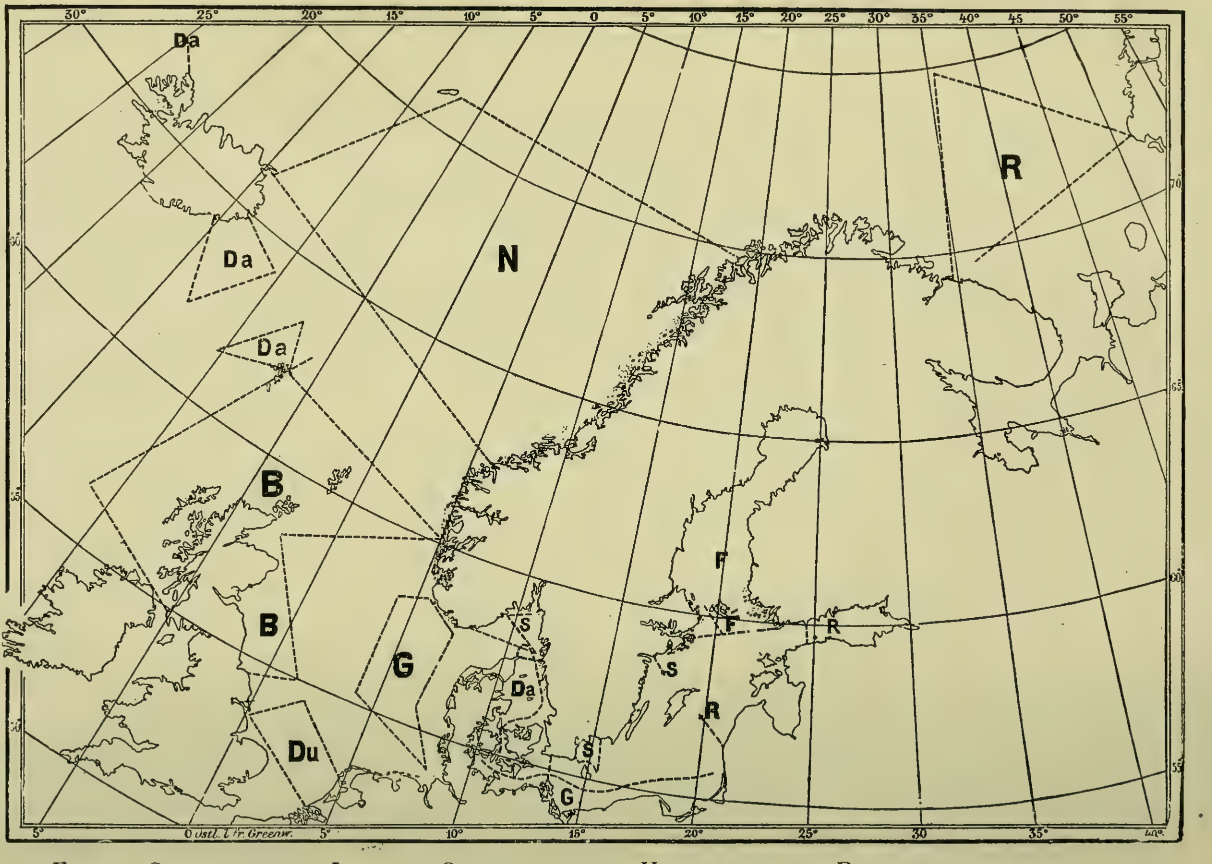


Fig. 7.—Chart showing Lines of Observation for Hydrographical Research proposed by the International Fishery Conference.

deep-water basins on either side of it—all this, of course, being in addition to the detailed exploration of the sea areas in immediate proximity to the European coasts.

The Wyville-Thomson ridge is known to separate two oceanic depressions with widely different physical conditions, and consequently a different fauna. Reference to these investigations is made elsewhere.

The International Hydrographic investigations have for their object the investigation of the physical characters of sea-water in this extensive area and even beyond it (Fig. 7).

The chief physical characters which it was essential to determine at the outset are (1) the temperature, at the surface and at intermediate depths; (2) the salinity—that is, the weight of solid saline matter in 1,000 grammes of sea-water; and (3) the nature and abundance of the gases (oxygen, nitrogen, carbonic acid, and sulphuretted hydrogen) dissolved in it. Other properties of sea-water are also of importance, but the hydrographic condition of a given volume of sea-water can usually be determined from the three characters given above. These characters vary from time to time in the same region—*e.g.*, the water on the Dogger Bank has different temperature and salinity in summer and winter; and also the water in different areas, such as the Faroe-Shetland Channel and the Cattegat, varies considerably. The determination of both temperature and salinity, simultaneously over the whole area, at periodic intervals was one of the first tasks of the International Council.

Each exploring vessel makes a special hydrographic cruise at regular stated intervals, and the vessels start as near as possible simultaneously. At the commencement of the investigations the cruises were made quarterly, the months chosen being February, May, August, and November. Each country had a special area allotted to it for investigation, and in the case of Great Britain these areas were again subdivided. Each of these areas and subareas was marked off in lines to be traversed by the research steamer on its quarterly cruise. On

each line a number of " stations " were selected. A station is a stopping-place for the exploring vessel at which the observations are made and the samples collected. The chart (Fig. 8) shows the lines investigated by the Lancashire Fishery Committee's steamer in the Irish Sea in 1909, with the observation stations numbered serially.

On reaching the station the steamer is stopped, a sounding made with the Lucas sounding machine, a sample of water is collected from the surface and at intermediate depths, these samples, after the temperature is recorded, being reserved for subsequent analysis at the shore laboratory. The chief routine determination is that of salinity calculated from the amount of chlorine per 1,000 parts of water as found by titration. The halogens are precipitated by nitrate of silver, and the total solids in solution calculated by means of hydrographic tables. The highest degree of accuracy is necessary, and this is only possible by means of control analyses made at the central laboratory at Christiania. The principal functions of this institution are the supply of instruments of research, the preparation of " standard " sea-water for checking the analyses made by the various national laboratories, and the preparation of the hydrographic tables. The observed and calculated temperatures and salinities are sent to the Bureau of the International Council for publication (*Bulletin des Résultats*).

Records are made on the charts of the areas under investigation, and in this way synoptical representations of the hydrographic condition of the sea are prepared. These charts of temperatures and salinities are pictorial representations of the circulation of the waters of the North Atlantic Seas from season to season and from year to year. The immediate cause of the water movements in the North Atlantic is the Gulf Stream circulation, which undergoes a periodic expansion and contraction. These gigantic annual pulsations are directly connected with the hydrographical phenomena of the seas of Northern Europe and the climate of the British Islands and Western Europe. A periodic flooding takes place

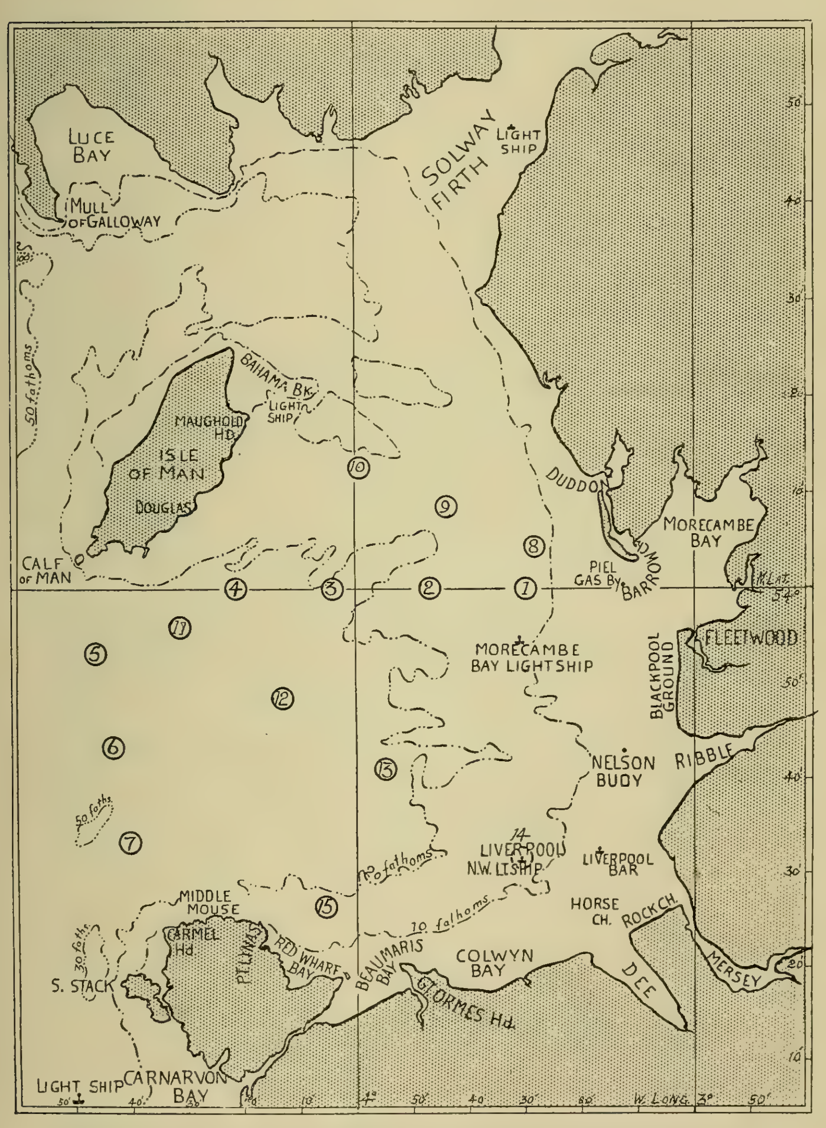


FIG. 8.—HYDROGRAPHIC OBSERVATION STATIONS, IRISH SEA, 1909.

of the North-Sea, the Skager-Rack, the Norwegian Sea, and even Barents Sea, with water of Atlantic origin.

The oceanic circulation in these waters is unquestionably dependent on the pulsations of the Gulf Stream. There is a continual drift of relatively warm and dense water from the south-west towards Northern Europe.

The following chart (Fig. 9) shows the observed conditions prior to the commencement of the international investigations (for August, 1896).

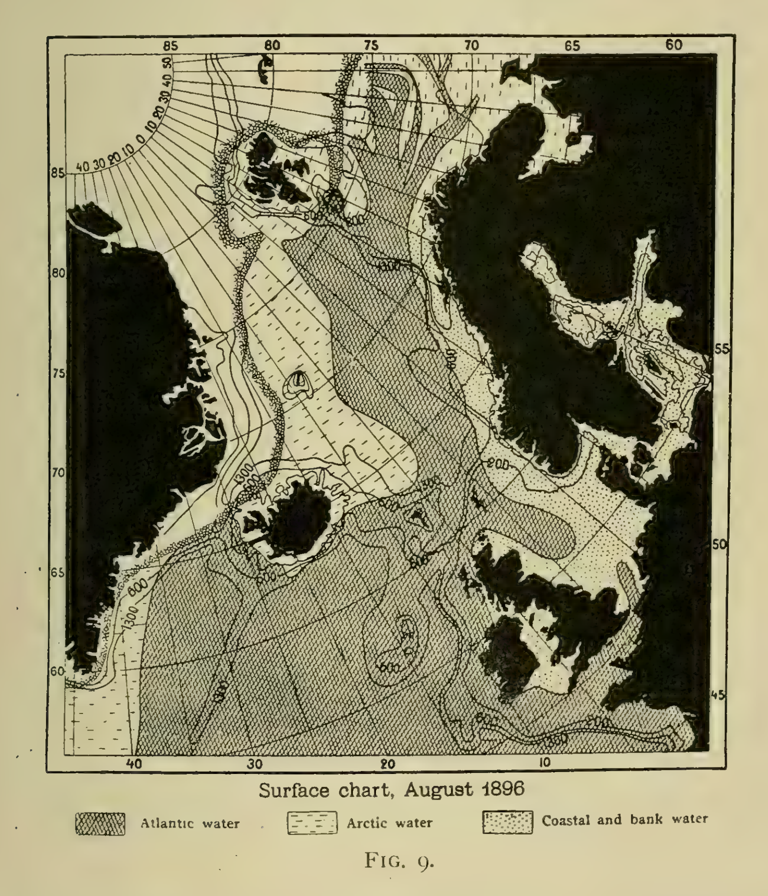
The chart shows what is probably the maximum flooding of the North Atlantic water by the Gulf Stream drift. The current has invaded the Icelandic coastal region, and has penetrated into Denmark Strait between Iceland and Greenland. Flowing on to the western coasts of the British Isles, the stream divides, part passing through the English Channel into the North Sea. The main stream passes on through the Iceland-Faroe and the Faroe-Shetland Channels. The international investigations, however, prove that not much Atlantic water passes through the former channel (Fig. 40). The whole of the oceanic basin south of the Iceland-Scotland ridge is filled with Atlantic water. When this warm and dense water impinges on the ridge only the surface portion of it passes over into the Norwegian Sea. After passing over this ridge, the "Norwegian branch of the European current" is deflected to the east, and a branch rounds the north of Scotland and enters the North Sea (Fig. 9).

Endeavours have been made to correlate the variations in temperature and salinity with the pulsations of the Gulf Stream drift, and as a consequence with the climatic variations of Western Europe and the distribution and migrations of commercially valuable species of fish, such as the herring and plaice.

It is manifestly impossible to give even in outline a summary of this important scheme of hydrographic research, and reference is made here only to the investigations in the Irish Sea area, it being understood that similar, or even more

extended, observations are made as far as possible simultaneously elsewhere in all Northern European waters.*

In the Irish Sea area semi-diurnal records are made of the surface temperature at the various light vessels, hourly records are made on the Lancashire Fishery Committee's investigation



Surface chart, August 1896

FIG. 9.

steamer *James Fletcher*, and in addition periodic hydrographic cruises are made by the same vessel, these cruises synchronising with those of other fishery research vessels—*i.e.*, those of Ireland and Scotland. The hydrographic cruises are usually

* Further details are given for various localities in the chapter on Ocean Currents.

made quarterly, and the sea temperatures are recorded, not only at the surface, but also at intermediate depths, by means of the Pettersson-Nansen water-bottle. The daily routine observations on surface temperature are made with "Kiel" thermometers, which are regularly checked with a Richter thermometer, which in turn had been compared with a standard hydrogen thermometer at the Charlottenburg Institute. On the quarterly cruises the deep-sea temperatures are observed by a Nansen deep-sea thermometer in case the Pettersson-Nansen water-bottle is used, or with a reversing thermometer of Richter with the Ekman water-bottle. The surface temperatures on the quarterly cruises (when a trained scientist is always present) are registered on a Richter thermometer. By this means records of a high degree of accuracy are obtained.

In the shallower parts of the Irish Sea the water is homothermous, except for small differences due to convection currents set up by the chilling of the surface waters and lateral shore drifts set up by winds.

Warm Atlantic water of high salinity can be distinguished flowing into the Irish Sea area. This is the so-called Gulf Stream drift. The amount of this water is greatest in the spring and least in the autumn, and its course up the Irish Sea bears no relation to the deep channel between Ireland and the Isle of Man and through the North Channel. This deep channel is a submerged river valley, and is not due to marine currents.

The Gulf Stream pulsates, and the amount of Atlantic water entering the Irish and North Seas varies from year to year. When the drift is at its maximum a current of water flowing northward strikes St. David's Head, and a portion is deflected southward (Fig. 10).

The climate of the British Islands undoubtedly depends to a certain extent on the strength of the Gulf Stream in any particular year.

When the Gulf Stream drift is weak less water of high salinity and temperature reaches our shores from the Atlantic,



FIG. 10.—CHART ILLUSTRATING THE PROBABLE DIRECTION OF THE CURRENTS IN THE IRISH SEA AND BRISTOL CHANNEL WHEN THE GULF STREAM DRIFT IS AT A MAXIMUM.

and in the Irish Sea a salinity maximum of only 34·2 is reached on the Holyhead-Calf of Man line, and that not until May. This happened in both 1909 and 1910, when we experienced dismal summers with little sunshine and much rain. An early salinity of over 34·4 in December, 1910, indicated a strong

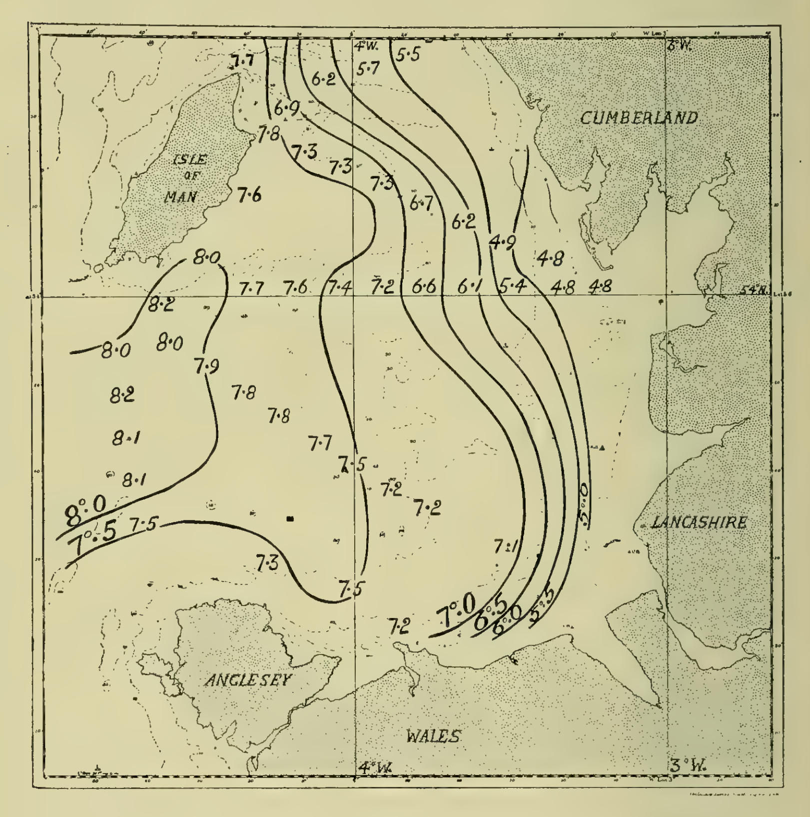


FIG. 11.—SURFACE TEMPERATURE IN THE IRISH SEA IN WINTER (FEBRUARY).

pulsation of the Gulf Stream drift, this being followed by the magnificent summer of 1911.

The connection between oceanic temperature and salinity on the one hand and the climate on the other has also been referred to in the case of Norway and Sweden (p. 190).

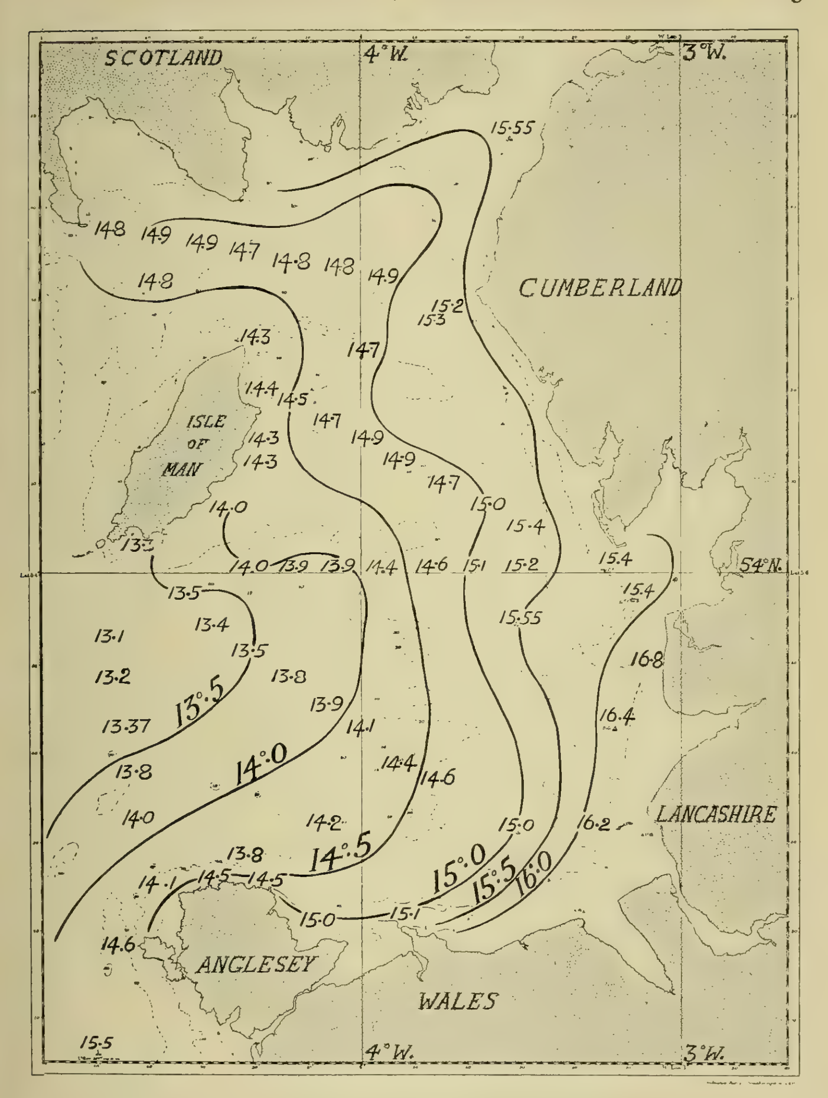


FIG. 12.—SURFACE TEMPERATURES IN IRISH SEA AT PERIOD OF MAXIMUM (AUGUST).

Endeavours have been made to trace a connection between fish migrations and sea temperatures in the Irish and other seas, but much additional information is required before reliable conclusions can be drawn.

In the Irish Sea the water is at its coldest in February. The progress of the drift from the Channel into Liverpool Bay is now clearly seen (Fig. 11).

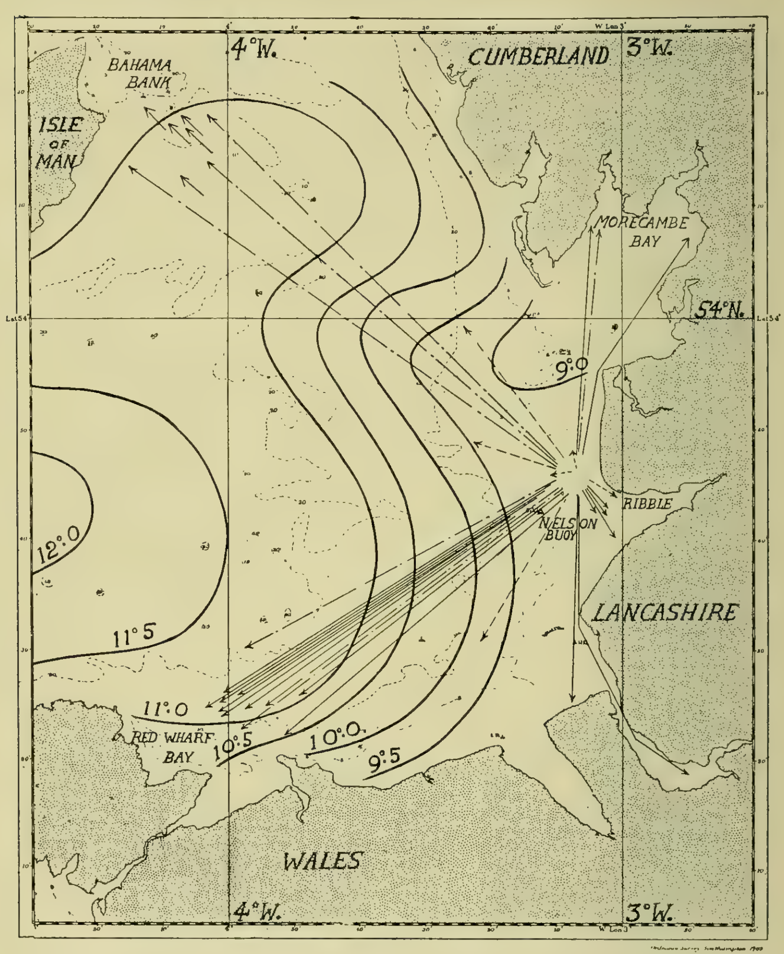


FIG. 13.—MIGRATION OF MARKED PLAICE IN THE IRISH SEA AND ITS RELATION TO WATER TEMPERATURES.

The period of maximum temperature is attained in August. The highest temperatures are now near the coast (Fig. 12), this being exactly the opposite of the conditions obtaining in winter. In the Irish Sea the sea is cooling down towards the

minimum in February, at a time when observation shows that local species of fish, such as the plaice, are not feeding. Consequently the migrations of plaice at this time must be due to some other cause than feeding. Johnstone says that there are optimal conditions of temperature for such fish as the plaice, and some at any rate of their migrations are due to the fish seeking the regions where such optimum temperature is to be found. The fish experiences a change of temperature, and may move in such a manner as to make this change minimal. In the summer plaice move out of water rising in temperature into colder water; in winter they move out of water falling in temperature into warmer water.

The next figure (Fig. 13) shows the migration of marked plaice from the Nelson Buoy fishing-grounds off the Ribble estuary. These fish were marked and liberated in June, the chart showing the recaptures made in the following October, November, and December, the isothermal lines being for the mid-month—*i.e.*, November. The broken lines represent recaptures in October, continuous lines those in November, and lines with dots those in December. The alongshore migrations represent capricious or aperiodic movements; they occur mainly in the winter. The main migrations are into Redwharf Bay, and also to the Bahama Bank off the Isle of Man, in each case from water of about 9° C. to 11° C. The details of the migrations, which cannot be shown on a single chart, prove this.

The Properties of Sea-Water.

Sea-water is distinguished from fresh water by its salt and bitter taste, which renders it unsuitable for drinking or culinary purposes. This taste is due to certain dissolved salts, of which the chief are common salt, magnesium chloride, magnesium sulphate, and calcium sulphate. Consequently sea-water is heavier than fresh water; and it gives an alkaline reaction. The amount of solid matter contained in sea-water is remarkably constant, especially if samples be collected far from land.

The mean quantity is approximately 35·976 grams in 1,000 grams of sea-water—that is, 3½ per cent. Sea-water has the properties of a dilute solution of salts—that is to say, as compared with fresh water it has a lower freezing-point and vapour tension, a higher osmotic pressure, electric conductivity, viscosity, and surface tension.

Sea-water is also an important medium for the development of organisms, both animals and plants; the latter can in the presence of sunlight build up organic from inorganic matter, thus playing an important part in the circulation of matter in the sea.

The Salts in Sea-Water.

Of the 80 elements known to modern chemistry, 32 have been identified in sea-water. Probably all are present, the majority in such small quantities as to elude identification. Of the 32, the following 7 are the most important: Chlorine, bromine, sulphur, potassium, sodium, calcium, and magnesium.

Analyses of sea-water give the following results. Those of Thorpe were from the Irish Sea, where the salinity is less than in the open ocean.

SALTS IN 1,000 GRAMS SEA-WATER.

	Thorpe.	Forchhammer.	Dittmar.
Common salt, $NaCl$	26·439	26·862	27·213
Magnesium chloride, $MgCl_2$ ...	3·151	3·239	3·807
Magnesium sulphate, $MgSO_4$ ...	2·066	2·196	1·658
Calcium sulphate, $CaSo_4$	1·332	1·350	1·260
Calcium carbonate, $CaCO_3$ ...	0·047	—	0·123
Magnesium bromide, $MgBr_2$ ...	0·070	—	0·076
Remainder (K_2SO_4 in Dittmar's table)	0·754	0·652	0·863
Total	33·859	34·299	35·000

Dittmar's and Forchhammer's analyses were made, the former from *Challenger* material collected from various parts of the world, the latter from water for the most part from mid-

Atlantic. Expressing the salts as percentages, we get the following table:

SEA-WATER: PERCENTAGE OF TOTAL SALTS.

	Forchhammer.	Dittmar.
Common salt, NaCl	78·32	77·758
Magnesium chloride	9·44	10·878
Magnesium sulphate	6·40	4·737
Calcium sulphate	3·94	3·600
Potassium sulphate	—	2·465
Calcium carbonate	—	0·345
Magnesium bromide	—	0·217

There are certain obvious differences in the results of these analyses, which differences are to some extent due to the method of expressing the results.

According to both Forchhammer and Dittmar, the relation in which the several salts stand to one another is constant. Both analysts determined the quantity of lime (CaO), magnesia (MgO), potash (K_2O), and sulphuric acid (SO_3) present with 100 parts of chlorine, including bromine, while Dittmar also estimated for soda (Na_2O) and carbon dioxide (CO_2). If the analyses are expressed thus, the above differences are no longer so appreciable. The following table gives Dittmar's and Forchhammer's analyses, together with some made by Schmelck on North Sea water:

	Forchhammer.	Dittmar.	Schmelck.
Cl	100·0 (Cl + Br)	99·848	100·0 (Cl + Br)
Br		0·3402	
SO_3	11·88	11·576	11·46
CO_2	—	0·2742	—
CaO	2·93	3·026	2·99
MgO	11·03	11·212	11·40
K_2O	1·93	2·405	—
Na_2O	—	74·462	—

Although samples of sea-water are never absolutely alike, there is, nevertheless, from all parts of the world a remarkable

similarity. . Practically the same ingredients are present, bearing nearly the same proportion to each other.

The salinity, or total weight in grams of dissolved salt in 1,000 grams of water, may be rapidly determined by titration with silver nitrate solution.

Another obvious method would be to evaporate off the water and weigh the resulting salts. This is difficult in actual practice, since in order to drive off all the water the heat applied drives off hydrochloric acid. The last portions of steam driven off in evaporation have also been found to contain appreciable quantities of carbonic acid as well, and the loss of these two substances reduces the total weight of the remainder, so that the titration method is preferred.

Since the ratio of the different salts in sea-water is practically constant, and since the halogens (chlorides and bromides) can be rapidly determined by titration with silver nitrate, it is possible to determine easily the chief physical characteristics of a given sample of sea-water.

For instance, the specific gravity depends on the salinity, and can be determined if the latter is known. The specific gravity of sea-water is its weight compared with an equal volume of pure water at the same temperature.

The density can also be determined from the same experiment. The density may be defined as the weight in grams of 1 c.c. of sea-water at the temperature *in situ*, t°, compared with that of 1 c.c. of pure water at 4° C. It is generally expressed as $S\frac{t^{\circ}}{4^{\circ}}$.

Tables have been prepared by the Danish hydrographer, Martin Knudsen, from which the ratios between salinity, density, and the halogens as determined by titration can be estimated. The salinity is determined with an accuracy of 0·05 per 1,000 parts, and the density up to 0·00004. According to Knudsen, the formula for conversion is—

$$\text{Salinity, } S = 0{\cdot}030 + 1{\cdot}8050\ Cl.$$

The quantity of dissolved salts in sea-water can be given approximately. Assuming the average density of sea-water, with an allowance for increase in the lower layers due to pressure, to be 1·04, the total weight of the seas would be 138×10^{16} metric tons. Allowing the weight of salt to be on the average $3\frac{1}{2}$ per cent. of this, the total weight of dissolved salts is $4{\cdot}84 \times 10^{16}$ metric tons. The volume of salt which would remain if the waters of all the oceans and seas of the world were evaporated depends on the specific gravity of the salts, which may be taken, on an average, to be 2·22. The volume of the salt would consequently be $2{\cdot}18 \times 10^{16}$ cubic metres, which if spread out on the floor of the ocean would give a depth for the salt layer of $196\frac{3}{4}$ feet, nearly 33 fathoms. This mass of salt is considerably more than the whole land volume of Africa (including Madagascar) above sea-level, or three times as great as the volume of Europe, or nearly half that of Asia.

The *density* of sea-water is of considerable importance from an oceanographical standpoint, since a great many ocean currents are clearly due to differences in the density of the layers of surface water.

The determination of the density of sea-water in a physical laboratory is not a particularly difficult operation, and full instructions for determining density are given in the various textbooks on practical physics. At sea, however, an instrument known as an aerometer is used. This is a hydrometer of glass, which, except for the long graduated stem, is completely immersed in the sea-water the density of which is desired. Glass, although more brittle than metal, has two advantages : it is less susceptible to increase in volume owing to changes of temperature, and it cannot be indented by rough handling. Since it is only desired to read densities from 1,000 to 1,031, it is possible to construct a scale for an aerometer to function between these densities. In order to allow of minute readings the scale would have to be a very long one, so it is found advisable to have a series of aerometers, usually six,

suitably graduated to read to the fourth decimal all densities between the above limits. Such an aerometer will give the density of the sea-water at the temperature at which the reading is made. A correction must be made to reduce the density to 4° C., the temperature of the maximum density of fresh water. The physical properties of sea-water are those of a dilute solution of salts. Modern theories of chemistry postulate for such solutions similar laws as for gases. When a fluid passes into the gaseous state its particles (molecules) are given off into space by a force known as vapour tension. The phenomena in a solution of salt in water are analogous, the force here being osmotic pressure. When a solid body is dissolved in water its particles distribute themselves by diffusion, a process which, however, takes place with greater difficulty than the diffusion of gases, and consequently is much slower.

Solutions of the same freezing-point have similar vapour tension and similar osmotic pressure.

Since solid bodies such as salts have a very low vapour tension, it follows that the temperature of the solution must be lowered below the freezing-point of the dissolving substance (in this case for water 0° C.) in order that the solution may begin to freeze. Consequently the freezing-point of sea-water varies with the amount of dissolved salts, and the greater the amount of salt the lower the freezing-point.

On the contrary, the boiling-point of sea-water is higher, for the same atmospheric pressure, than that of fresh water. For the relationships between vapour tension, osmotic pressure, lowering of the freezing-point and raising of the boiling-point, textbooks on physical chemistry should be consulted. There is a direct connection between these properties, so that if one be known or estimated the others can be deduced. Of the above four properties, there are considerable practical difficulties in the correct estimation of three—namely, vapour tension, osmotic pressure, and boiling-point. The estimation of the freezing-point of sea-water is easier and has been done with a high degree of accuracy,

especially by Knudsen, who found that sea-water of salinity 2·4695 per cent. has its maximum density at its freezing-point, $-1·332°$ C.

Knudsen has published tables giving the relationship between the freezing-point, density, and osmotic pressure for water of different degrees of salinity. Although the discussion of these relationships is beyond the scope of this work, there is one point of practical importance to the biologist that must be mentioned. If a frog is placed in sea-water, it loses at once by osmosis, through its skin, large quantities of water, and soon loses one-fifth of its original weight. On the contrary, a true sea fish suddenly plunged into fresh water quickly absorbs water, and, in fact, speedily dies from a kind of dropsy.

The osmotic pressure of sea-water varies with the increase of density. Water from the Baltic of 7·5 per 1,000 salinity has at a temperature of 18° C. an osmotic pressure of 4·9 atmospheres, while water of the Red Sea of 40 per 1,000 salinity at 30° C. has osmotic pressure of 26·7 atmospheres.

The following table gives the boiling-point and vapour tension for sea-water of different degrees of salinity:

Salinity, per cent. ...	5	10	15	20	25	30	35	40
Boiling-point, increase °C	0·08	0·16	0·23	0·31	0·39	0·47	0·56	0·64
Vapour tension decrease, mm. ...	2·13	4·23	6·45	8·47	10·73	12·97	15·23	17·55

From the above considerations it follows that sea-water, under the same conditions, evaporates more slowly than fresh water, and the higher the salinity the slower the evaporation. The variations in the surface salinity of sea-water depend on the relation which evaporation bears to rainfall, and since the sole source of atmospheric moisture is practically the sea, the inter-relationships of salinity, evaporation, and atmospheric moisture are of great importance. On the last depends rainfall, the vegetation of the earth's surface, and incidentally the distribution of population. The fact that evaporation from sea-water is much less than from fresh has long been known,

although the early estimates of the difference were much too high.

The best comparison between the evaporation of salt and fresh water is probably that made by the Japanese investigator, Okada, whose researches extended over seven years. He found that, on the average, sea-water evaporation was about 95 per cent. of that of fresh water, the annual variations ranging from 92·6 to 96·8 per cent.

In Japan the average daily evaporation of sea-water was 3·44, and for fresh water 3·27 mm., the maximum being in August (6·00 and 5·69 mm.), the minimum in January (1·97 and 1·03 mm.).

Okada also investigated carefully the influence of the air temperature and sunlight on evaporation.

Textbooks on meteorology give the following chief influences on the rate of evaporation :

1. Atmospheric pressure.
2. Atmospheric temperature.
3. Atmospheric humidity.
4. Atmospheric movements—*e.g.*, wind.
5. Variations in water salinity.

Evaporation takes place more quickly at a lower pressure of the air, and also the higher the temperature. The less the humidity the greater the evaporation. With strong winds the evaporation also increases, and, as already stated above, the greater the salinity the less the evaporation. Sunlight has also an important effect on promoting evaporation, and according to Okada evaporation proceeds on the average nearly two and a half times more quickly in sunlight than in the shade.

This agrees with Mill's results, obtained on observation of the evaporation of fresh water in Camden Square, London, where the evaporation was found to be directly dependent on the amount of sunlight.

Optical Characters.

Anyone who has taken a long sea voyage will not have failed to notice that sea-water is characterised by great clearness and a peculiar colour. The manner in which light penetrates sea-water has a direct bearing on the environment of marine organisms of all kinds, and the two most important questions for consideration are the refraction and absorption of light.

Water being a denser medium than air, a ray of light falling from the air into water is bent towards the perpendicular. The index of refraction for yellow light in fresh water is 1·333, and this index increases with the salinity, but decreases with the temperature.

The *transparency* of the sea varies considerably from place to place. As a general rule, vessels lying at anchor in the tropics can see the anchor on the bottom in depths of 10 fathoms and upwards, but in temperate seas this is not possible, although Captain Hood in 1676 observed mussels on a bottom of white sand at Nova Zembla in a depth of approximately 80 fathoms (? a mistake for 80 feet). Regular observations on the transparency of different seas have been made from time to time, the first of which are due to the Russian scientist Kotzebue on the *Rurik* in the tropical waters of the North Pacific Ocean. He found a red cloth disappeared in depths of from 11 to 16 fathoms, whereas a white plate was visible down to 27 fathoms. The American naval officer, Charles Wilkes, made numerous observations with a white basin, and he noted not only the depth of disappearance, but also the depth at which it again became visible when being hauled in. He also noted the height of the sun during the observation. In the tropical parts of the Pacific he found good visibility down to depths of 16 to 32 fathoms. Observations are on the whole more successful the nearer the eye is to the surface of the water. Other observations show that yellow discs have a visibility of 88 per cent., red 77 per cent., and

green only 67 per cent., of similar white discs. In the Irish Sea the maximum visibility is about 12 fathoms. As a rule the visibility is greatest at sunrise and sunset, and decreases with the height of the sun.

A second method of determining the transparency of sea-water is to sink an electric light on a dark night, observe the depth at which the lamp itself disappears, and also the depth at which the diffused light is no longer visible. This has been done by Spindler and Wrangell in the Black Sea in localities where the depth was well over a thousand fathoms. The greatest depth at which the lamp (of 8 candle-power) was visible was a little over 21 fathoms, whereas diffuse light was still noticeable at 35½ fathoms.

Still another method is the photographic. Sensitive plates are exposed at varying depths until after long exposure they cease to darken. By this method the presence of light has been detected, off Capri, at depths of 270 to 300 fathoms.

More recently an improved photometer has been devised by Helland-Hansen, and used in the Norwegian investigations on the *Michael Sars*. A camera of special construction is lowered to the required depth while hermetically sealed. A messenger runs down the line and detaches the bottom part of the camera in which the plates are exposed. After the required interval a second messenger runs down the line which, in effect, puts the lid on the camera, which can then be drawn up to the surface.

Highly sensitive panchromatic plates are used, and with Wratten and Wainwright's three-colour filters (red, green, and blue) it is possible, when required, to exclude certain portions of the spectrum.

Helland-Hansen's experiments show that a plate exposed for 80 minutes at 1,000 metres (546 fathoms) was blackened by rays of light, but an exposure for 120 minutes at 1,700 metres (940 fathoms) produced no result. It follows that the limit to which light penetrates lies somewhere between these limits.

The fact that light penetrates to an appreciable extent down to 550 fathoms was not previously suspected.

Regnard has devised an apparatus for determining the length of the day at different depths, a photographic film on a cylinder being passed by a clock-work arrangement before an aperture in the "camera." Experiments made at Madeira showed that at 11 fathoms the day lasted 11 hours, at 16½ fathoms 5 hours, but at 22 fathoms, although the sun was shining brightly, the film only exhibited a slight influence of light for a quarter of an hour about 2 p.m.

As a general rule pure water is less transparent the higher the temperature. In spite of this, the tropical seas are more transparent than the temperate. Salinity does not appear to be of much importance in this connection. The Baltic and North Seas are of like transparency but very different salinity, and the same is true of the Red and Sargasso Seas.

The *colour* of the ocean has been the subject of frequent misunderstandings and misdescription. Reflection from the surface causes the various differences described by different writers and painted by different artists.

Omitting reflection from consideration, the colour of local seas is green, that of the tropical seas, on the other hand, blue. Occasionally the colour of the sea takes on a whitish, yellowish, reddish, or olive-coloured tint, but these appearances are invariably due to the presence of suspended matter or of organisms. The normal colour of the sea is consequently either green or blue.

For the exact determination of the colour of the sea various instruments and methods have been applied, of which one only need be mentioned here. Forel invented a scale or xanthometer which indicates all colour changes from pure yellow through green to deep blue. Two solutions were made, the first of 1 gram of copper sulphate with 9 grams of ammonia and 190 grams of water; the second of 1 gram of neutral potassium chromate in 199 grams of water. The first solution was taken as the index and was numbered 0. Then mixtures

were made in the following proportions: two of yellow to 98 of the blue (2), five of the yellow to 95 blue (5), and so on. These solutions were enclosed in glass tubes of 1 centimetre diameter, and then arranged like the rungs of a ladder. The comparisons take place in the absence of direct sunlight or of light reflected from the heavens. Up to the present not many colour investigations with Forel's scale have been made in the open oceans. The greatest surface of mid-ocean shows a blue colour, 0 to 2 on Forel's scale, especially in tropical and subtropical regions. Green colours are met with near the coast and in shallow water generally, and again in Polar waters. The North Sea in its northern and central portions is dark blue. The purest and deepest blue is that of the Sargasso Sea, although the South Atlantic, Indian, and Pacific Oceans are not very different.

Small quantities of sea-water are colourless both by reflected and transmitted light. Greater depths appear blue by transmitted light, according to the experience of divers. In depths of 13½ to 16 fathoms a dark red animal appears black to a diver; on the contrary, the green or bluish-green algæ appear paler than usual. This is because sea-water absorbs the red rays much more strongly and rapidly than the green.

The absorption of light in sea-water plays an important rôle in the life-history of marine animals and plants. It has been estimated that at a depth of 96¾ fathoms yellow light has the intensity of the light of the full moon on the surface of the land.

The power of assimilation of marine plants varies considerably. For instance, the Rhodophyceæ assimilate nearly two and a half times as fast in the blue rays of the spectrum as in the yellow. Consequently algæ of this group are found flourishing in greater depths than others. The conditions under which the algæ of the plankton, with their yellowish or brownish corpuscles, assimilate is not thoroughly understood. One species (*Halosphæra viridis*) is, however, met with living in depths of over 1,000 fathoms, both in the Mediterranean

and the Atlantic. Most abyssal animals—*e.g.*, fish (except those which live embedded in the mud of the floor of the ocean)—possess eyes, and consequently can see either by means of the phosphorescent light which is present at these depths, or by such extremely small quantities of violet light which penetrate to depths of thousands of fathoms. These indigo-blue rays would not be perceptible to the human eye.

The bluest of all seas, the Sargasso, is also the poorest in floating organisms (plankton), so much so that " deep blue is the desert colour of the deep sea." Not only does the plankton minimise the transparency of the sea and so make it greener, but in many cases the colour of the large masses of particular organisms which are sometimes present imparts a decided tint to the sea. The chromatophores of the plankton plants, such as diatoms and Peridineæ, are yellow to brown, and when pelagic diatoms are present in large quantities the whole sea appears cloudy. In the main oceans changes of colour due to plankton are not frequently met with, though occasionally a greenish tint is noticed at certain periods at places which are usually deep blue in colour. Hudson (1807) noticed in northern waters that the colour was olive-green, this being due to the presence of diatoms, and a similar phenomenon due to the same cause was noted by James Ross in Antarctic waters.

The red colour frequently observed in the Red Sea is due to masses of an alga (*Trichodesmium erythræum*). A yellowish colour due to a yellow-brown alga has also been observed in Arafura Sea, not far from the mouth of the River La Plata (South America). The sea is frequently tinted blood-red; in this case the colour is due to the presence of minute marine Crustacea (Copepoda). A certain species of these Crustacea (*Calanus finmarchicus*) abundant in northern waters produces a similar coloration north of the Bank of Newfoundland. In the blue Gulf Stream water between the Azores and the Bank of Newfoundland green layers have been observed to be due

to the presence of a minute phosphorescent medusa (*Pelagia noctiluca*).

Variations in the colour of the sea due to the presence of minute inorganic particles in suspension have not been observed with any frequency, at any rate apart from localities in direct neighbourhood of the coast. The Gulf of California during the rainy season is coloured by the waters of the Rio Colorado.

In the English Channel, after several days of stormy weather, the water takes on a milky-green appearance, due to minute chalky particles in suspension.

Off the mouths of tropical rivers the sea is coloured for miles. The Congo and Amazon furnish good examples, the muddy yellowish water being in marked contrast to the deep blue of the open ocean.

Other characteristics of sea-water which must be briefly mentioned are—

1. Specific heat and conductivity.
2. Surface tension.
3. Viscosity.
4. Compressibility.
5. Electrical conductivity.
6. Radioactivity.

Specific Heat and Conductivity.

The specific heat of a substance is the amount of heat, expressed in calories, necessary to raise 1 gram of the substance through a degree of temperature (Centigrade). It is now customary to take the amount required to raise the temperature from 14·5° to 15·5° C. The salts dissolved in sea-water have a lower specific heat than that of fresh water; consequently the specific heat of sea-water is less than that of fresh water. The specific heat of sea-water of different degrees of salinity has been carefully estimated by the French oceanographer, Thoulet.

The specific heat of sea-water at 17·5° C. may be taken from the following table :

Specific Heat of Sea-Water.

Salinity (per mille) ...	0	5	10	15	20	25	30	35	40
Specific heat	1·000	0·982	0·968	0·958	0·951	0·945	0·939	0·932	0·926

The specific heat of sea-water is less than would be expected from the nature and amount of the dissolved salts.

The heat conductivity of sea-water has not been determined practically, but from theoretical considerations the following table is constructed, compared with fresh water expressed as 2,000 (really ·0020) :

Salinity (per mille)	0	10	20	30	35	40
Conductivity	1400	1367	1353	1346	1341	1337

The *Surface Tension* of sea-water is of considerable importance to the study of oceanography. Every liquid may be regarded as bounded by a surface film which behaves like a stretched membrane, and sea-water is no exception. The surface tension plays a part in the formation of the smallest waves, and it increases with the salinity.

Viscosity.

According to one theory, surface currents due to winds are helped to spread to the deeper layers by the viscosity of the sea-water. The viscosity of salt water is higher than that of fresh, but is considerably diminished at higher temperatures, so much so that in tropical seas of a temperature of 25° C. and upwards the viscosity is only half of that observed at 0° C. In the deeper layers of ocean waters the viscosity may be higher on account of the increased pressure, but it has not been ascertained experimentally.

A rise of 1 per cent. in salinity only causes an increase of 2 to 3 per cent. in the viscosity, and since the salinity of sea-water does not vary much it follows that it is the changes of temperature which produce changes in viscosity.

These changes in viscosity are associated with differences

in the suspension organs of marine plants. The small marine plants which are found floating practically everywhere in the upper layers of the sea, at any rate to the depths to which light penetrates, are provided with contrivances to prevent (or at any rate to hinder) them from sinking below the light level, where they would die. These contrivances are termed suspension organs, and are of four main types :

The *Bladder* type, in which the cells of the plant are very large, the protoplasm forming a thin layer round the inside of the cell wall, the centre of the cell being filled with a fluid of about the same specific gravity as sea-water (*e.g.*, Coscinodiscus).

The *Ribbon* type, where the surface is enlarged owing to the cell being flattened and even bent or twisted (Fragilaria).

The *Hair* type, where the cell is much prolonged in one direction (Rhizosolenia).

The *Branching* type, in which the surface of the cell is enlarged by various hair-shaped or lamelliform outgrowths (species of Chætoceras).

Now, the curious thing is that some of these species of marine plants of wide distribution develop an external form in accordance with the viscosity of the water in which they find themselves. Formerly these plants were thought to be distinct species. A good example is *Rhizosolenia hebetata,* found both in Arctic and Atlantic waters. In the Arctic, where the water is cold and viscosity high, this plant is thick-walled and gross ; in the Atlantic, where the water is warmer and viscosity less, this plant, in order to protect itself against the greater tendency to sink, develops thinner walls and is proportionately longer, being furnished with a long hair-like spine at each end. Transitional forms are met with which are obtuse (hebete) at one end and spiny at the other.

Compressibility.

Liquids, as a rule, are not compressible. Tait gives the compressibility of pure water to that of sea-water from the

Firth of Forth as 100 : 92·5; and pure water compared with sea-water taken outside the Firth as 100 : 92. The transmission of waves of sound through water depends on the non-compressibility of the water. Sound travels through water four times as rapidly as through air.

Electric Conductivity and Radioactivity.

If the electric conductivity of pure water be taken as nil, then that of sea-water at 0° C. and of salinity 35 per mille will be 0·0293 ohms. Radioactivity is not observable in sea-water.

SEA-ICE.

In the neighbourhood of the Poles the temperature of the sea is so low that large areas become frozen. This sea-ice, together with river and glacier ice derived from the land, is influenced by the prevailing ocean currents, and is met with, especially in the form of icebergs, distributed over extensive areas in high latitudes in both the Northern and Southern Hemispheres. Of the three kinds of ice mentioned, river-ice is the least important. It is missing altogether in the Antarctic regions, where there are no rivers; in the Arctic it is formed in the great rivers of the Siberian and North American plains.

Sea-ice is frozen sea-water. Sea-water does not freeze at 0° C. (p. 72), but at an appreciably lower temperature, this temperature depending on the salinity. Ground-ice is frequently formed in shallow water close inshore in the Baltic before the surface water is frozen over. In winter the fishermen's nets are frequently hauled in covered with ice and with the fish entangled quite frozen.

The formation of *field-ice*, as the flat ice formed inshore is called, prevents, or at any rate hinders, the freezing of the sea to any great depth—firstly because the ice is a bad conductor of heat and prevents the loss of heat from the underlying water by radiation, and secondly because the salts extruded from the field-ice make the underlying water of higher salinity and consequently lower freezing-point. The specific weight of

pure ice is, according to Bunsen, 0·9167; for sea-ice it varies from 0·903 to 0·959; probably 0·92 is a fair average.

The rate of growth of sea-ice in thickness has been calculated from theoretical considerations. With an average temperature of 5° below the freezing-point of sea-water ice forms at the following rate: for 100 days 71 centimetres; for 200 days 100 centimetres. If the temperature fall to 20° below, then the ice thickness is after 100 days 142 centimetres, after 200 days 201 centimetres, and after 300 days 246 centimetres thick. Ice-shoals of one winter's growth are rarely more than 2 metres thick, and scarcely ever exceed 3 metres. In Antarctic regions from 1 to 1½ metres is the rule, since here the temperatures are not so low and the salinity is higher than in the Arctic. Accurate observations on the rate of growth of sea-ice have been made by Drygalski. At first the growth is very rapid—from the 2nd to the 20th December 25·4 centimetres; from the 20th December to the 19th February 56·4 centimetres; to the 22nd March 73 centimetres; then to the end of May 72 centimetres; after which in June it rapidly commenced to melt.

Snow is a bad conductor of heat, its coefficient being about one-tenth that of ice. So there are strong agencies preventing the freezing of the sea below a small depth.

The field-ice, which is usually formed near the shore, soon becomes disturbed by wind and sea, and it becomes uneven. *Floe-ice* consists of several pieces of field-ice frozen or pressed together. *Pack-ice* is formed from broken-up floes which have to a certain extent closed together again. This pack-ice is superficially very uneven, as it is driven together and heaped up by winter storms. When there are leads or lanes of water forming more or less navigable channels the pack-ice is said to be *open;* when it is not possible to navigate the pack, it is said to be *close*. This pack-ice, which is in constant movement, exercises considerable pressure on ships embedded in it—in fact, unless ships are specially built to withstand this pressure, as was Nansen's ship the *Fram*, there is considerable danger

of their being crushed to pieces. When the edges of ice floes are forced together in strong breezes, *hummocky ice* is formed. The pressure of pack-ice is not, however, altogether due to wind, but to the further cooling of the ice itself. According to Otto Pettersson, sea-ice, unlike all other bodies, on being subjected to further cooling expands. At first the expansion is rapid, from – 10° C. slower, until at – 20° C. sea-ice maintains an approximately constant volume. So the pack-ice continues to exert pressure in sharp frosts even when the weather is quite settled. The firmness of sea-ice shows the greatest variation. *Pancake-ice* is newly-frozen ice of sufficient thickness to prevent navigation, even though it will not support a man's weight.

Pack-ice disappears very rapidly in the Arctic regions in summer. The chief factors in its disappearance are evaporation from the surface, the movement of the water, the long Arctic days of summer, and the reflection of the heat of the sun from the rocky coasts. Instead of the *ice-foot,* as the ice frozen to the shore is called, there is in summer a lane of water round most of the Arctic islands and continental land, in which whaling and exploring vessels are able to make considerable progress.

Fog and rain also exercise considerable influence. In Antarctic regions the factors which make for disappearance of the pack-ice are not so favourable.

The Geographical Distribution of Sea-Ice.

In the first place pack-ice may be considered, leaving icebergs to be dealt with later. The greatest extent of pack-ice is met with in the Arctic Ocean. The maximum extent is generally in May, the minimum in August, though there is considerable variation from year to year. In May most of the land bordering the Arctic Ocean is fringed with pack-ice, the most notable exceptions being the whole coast of Norway right round the North Cape to Cape Sviatoj, which is never covered; the south coast of Iceland, and the west coast of Greenland.

The pack-ice, when it breaks up on the approach of summer, spreads out in two main currents into the open ocean, where it speedily melts. Of these two, the East Greenland Current is the more important; it is estimated to distribute two and a half times the amount of pack-ice to that of the current from Baffin Bay, the West Greenland Current. The area between Spitsbergen and Greenland is always, both summer and winter alike, more or less filled with pack-ice. It is not a continuous layer. The reflection of the sea's surface seen in the sky produces two impressions; an effulgence near the horizon indicating ice is the so-called *ice-blink;* open water reflects a dark *water-sky*.

The White Sea is filled in winter with a land-floe; east of this the pack-ice boundary runs in winter towards Nova Zembla, most of Barents Sea being fairly open water. The pack-ice boundary in May runs in a curve roughly south-west from Prince Charles's Foreland in Spitsbergen to the north-east coast of Iceland, Jan Mayen Island being within the pack-ice.

No pack-ice comes out through Bering Strait. In Bering Sea the pack-ice renews itself every winter, so that in May it practically fills up Bristol Bay, and thence its boundary runs across via St. Matthew Island (Pribiloffs) to the Asiatic coast, which it cuts at about 60° N. Lat. and 170° E. Long. By August the ice has shrunk considerably, and in particular there is a run of more or less open water right round the continental land.

The west coasts of Spitsbergen and Nova Zembla are almost entirely free from pack-ice in the height of summer, and the lane of water up the west coast of Greenland has considerably extended.

Icebergs.

Icebergs are floating masses of ice which have been split off from land glaciers. They are formed in both Arctic and Antarctic regions, though under somewhat dissimilar conditions,

with the result that their appearance differs considerably in Northern and Southern Hemispheres.

The Arctic icebergs originate on the west coast of Greenland, where the coast is rugged, precipitous, and characterised by deep glacinated inlets or fiords. These fiords are the birthplace of icebergs, which break away from the terminal portion of the glaciers. According to Rink, there are five principal ice-fiords on the west coast of Greenland between 67½° and 73° N. Lat., every one of which receives annually many thousand cubic feet of ice. These fiords are, from south to north—Jakobshavn, Torsukatak, Karajak, Kangerlugsuak, Umanak, and Upernavik. Other glaciers which give rise to icebergs are Humboldt Glacier, between Smith Sound and Kennedy Channel, and Petovik Glacier, between 76° and 76½° N. The largest icebergs are split off from the extremity of glaciers which reach the sea on a gentle slope.

The splitting off an iceberg from the glacier's extremity is termed "calving." The glacier protrudes seaward until by sea disturbance, by its own weight, or by some other agency, equilibrium is destroyed and the iceberg breaks off. Since many of the fiords are shallow at their seaward extremity, many of the icebergs become stranded on the so-called iceberg banks. The height of Greenland glaciers has frequently been measured. Bergs over 300 feet high are rare—in fact, those over 200 feet are noticeably high. There are, however, records up to 800 feet (by the steamer *Principello* in April, 1915), or even 1,000 feet (steamer *Marie*, May, 1906). Whether these latter records are based on careful trigonometrical calculations is doubtful, and such heights should only be accepted with reserve.

According to Steenstrup, the portion of the ice above water bears to that below water a proportion of from 1 : 7·4 to 1 : 8·2. As a rule it may be assumed that a tabular iceberg floats with from one-seventh to one-ninth of its bulk above water. Krümmel gives 1 : 8 as one extreme and 1 : 4 the other, and

as good averages from 1 : 5 to 1 : 6, in this respect differing considerably from British estimates.

Icebergs drift south from Smith's Sound into Baffin's Bay, and to these the Arctic giants belong, those from the Umanak and Jakobshavn district being as a rule much smaller. The principal source of the icebergs of Baffin's Bay and the Labrador Current is, then, North-West Greenland, only a few coming from the east side, via the East Greenland Current. These latter have to round Cape Farewell before they get into the Labrador Current.

Icebergs disappear gradually under the same influences which cause the melting of the pack-ice, the under-water influence being chiefly a high sea, the aerial influences sunlight, rain, and fog.

The Greenland icebergs are carried down, together with a certain amount of pack-ice, by the Labrador Current over the Newfoundland Banks to 45° N. and lower. The monthly distribution of both icebergs and pack-ice throughout the year on the Banks is shown on the Monthly Meteorological Charts of the North Atlantic. The melting of this ice appreciably lowers the temperature and salinity of the surface water in these regions. Since each iceberg swims, as it were, in its own cold-water bath, it is frequently possible to detect the presence of an iceberg in thick weather by the sudden drop in the temperature of the surface water.

Icebergs which drift below 40° N. Lat. or to the eastward of 40° W. Long. must be regarded as exceptional. There are twenty-one authentic records from the commencement of the twentieth century up to July, 1916, a period of fifteen and a half years. The position of these is shown on the appended chart (Fig. 14).

Icebergs are never met with off the Norwegian coast, or off the coast of Siberia, or in the North Pacific.

The Antarctic is the region *par excellence* for icebergs. Here they are calved almost anywhere along the great ice barrier which marks the limit of the land of the Antarctic

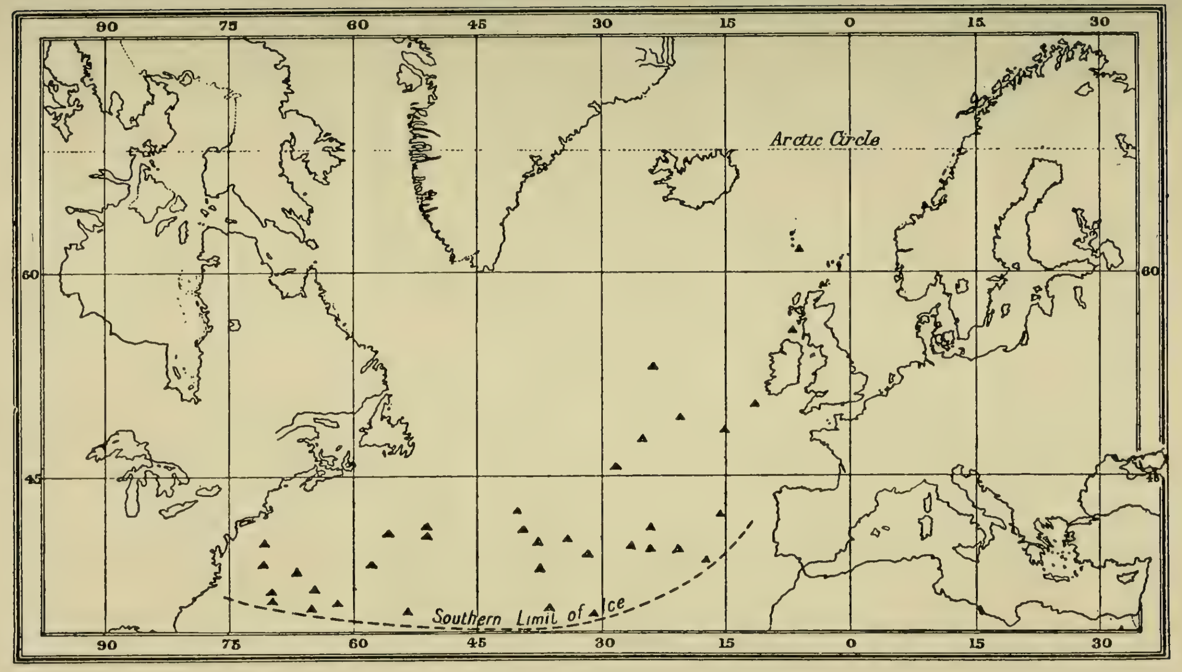


FIG. 14.—NORTH ATLANTIC ICEBERGS: PHENOMENAL DRIFTS.

continent. Sir James Clark Ross, who discovered a continent south of 70° 30′ S. Lat. and west of 171° E. Long., sailed for over 400 miles along an ice barrier, the height of which was estimated to be from 150 to 200 feet.

Captain Charles Wilkes, of the U.S. Navy, who visited the Antarctic prior to Ross, discovered land and ice barriers between 67° and 64° S. Lat. and 160° and 76° E. Long. in several localities. He averaged the ice-cliffs to be from 150 to 250 feet high, and describes icebergs afloat near the barrier as from a quarter of a mile to five miles in length.

The Antarctic icebergs are tabular in form and often of phenomenal height, 800 feet being by no means unusual, and heights of 1,700 feet are recorded. These bergs are sometimes so large as to receive the name of *ice islands*. They naturally take longer to melt than the Arctic icebergs. The Arctic bergs seldom last over two years, whereas the larger Antarctic bergs probably last at least ten.

Between 1891 and 1916 there are six records of Antarctic icebergs of 50 miles length or more; of these, the largest were those reported by the *Ethelbert* in March, 1893 (82 miles), and by the *Antarctic* in November, 1894 (70 miles).

The general northern boundary to which the Antarctic icebergs drift is 45° S. Lat. The boundary-lines are bent seawards off the east coast of South America. Icebergs are met with farther north to the eastward of Cape Horn than elsewhere, from Cape Horn (55° W. Long.) right round to 120° E. Long.; they rarely drift north of 40° S. Lat. From the South Australian coast in 120° E. Long. round past the Cape of Good Hope to Cape Horn again they drift on the average to 35° S. Lat. (Fig. 15).

Atmospheric Gases in Sea-Water.

Water, either fresh or salt, absorbs gases from the atmosphere, and, in fact, sea-water may be considered to have atmospheric gas in solution. There are two kinds of solutions. In the one the absorbed gases are liberated by a decrease in

the atmospheric pressure or by an increase in the temperature of the water; in the other this is not the case, and the solution in this latter case is not purely physical, but must be of a chemical nature. Both kinds of solution are met with in sea-water. For the most part, the oxygen, nitrogen, and argon

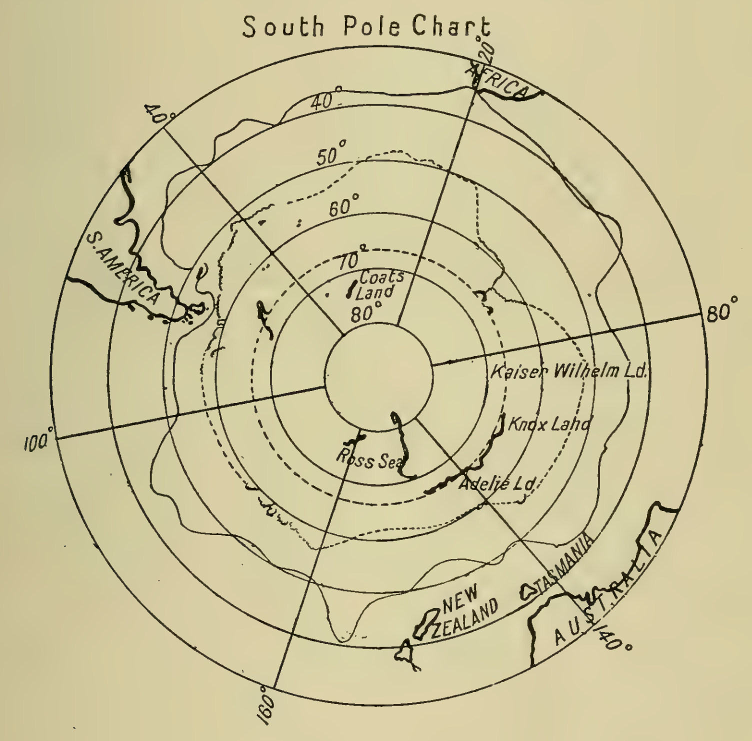


FIG. 15.—SOUTH POLAR ICE LIMITS.
———— Outer limit of icebergs.
.... Outer limit of pack-ice.

of the atmosphere are absorbed according to physical laws, but the atmospheric carbon dioxide, partly at any rate, is absorbed not strictly in accordance with these laws, and so its solution falls into the second class above mentioned.

The conditions under which gases are absorbed by water are set out in detail in textbooks of physical chemistry.

An important feature of absorbed air may be noticed here. In air the proportion, by volume, of oxygen to nitrogen is about 21 to 78, or roughly 1 to 4, but in water at 0° C. the absorbed gases are present in the proportion of 34·6 to 61·8, or roughly 1 to 2. So that marine organisms breathe in a much higher proportion of oxygen than land animals. On the other hand, a land animal which has inhaled 1,000 c.c. of air will have passed into its lungs 210 c.c. of oxygen, but a fish which has passed a similar quantity of water over its gills will thereby have had access to 10 c.c. only of oxygen. Anyone who has kept fish in aquaria will have been struck by the small quantity of oxygen required to sustain life. As a rule solutions of salt have a smaller coefficient of absorption than pure water, although in certain solutions the atmospheric gases may enter into chemical combination with the salts, and so a higher power of absorption is exhibited. This is especially the case with carbon dioxide.

A great deal of work on the determination of the atmospheric gases dissolved in sea-water has recently been done, under the auspices of the International Council for the Investigation of the Sea, by Jacobsen and Fox. As a rule two samples of water are required, one for an estimation of oxygen and nitrogen, the other for the carbonic acid. The estimation of these gases is extremely technical, and for the details the original papers published by the Council should be consulted.

Dissolved oxygen and nitrogen are met with in sea-water, not only in the surface layers, but also in great depths. For nitrogen the proportion absorbed by the deeper layers is what one would calculate for a surface water of similar density and temperature, and from this it is concluded that the bottom layers of water were once in contact with atmospheric air at the surface. For oxygen the calculated and observed results in deep water differ considerably, there being always a deficit in the observed results. This is doubtless due to the fact that the oceanic animals have utilised a part of the oxygen for

respiration. In some cases the surface layers have an excess of oxygen over the normal, and this, again, is to be attributed to a biological cause, the liberation of oxygen by the planktonic plants in the process of assimilation. Carbon assimilation takes place in plants provided with chlorophyll, in the presence of sunlight, the atmospheric CO_2 being utilised, the carbon assimilated, and the oxygen liberated. Nitrogen, a relatively inert gas, is much more evenly distributed in the waters of the ocean, although here, again, a variation is met with due to biological influences. Denitrifying bacteria are found in sea-water, and are more active in the higher temperatures of tropical seas. These bacteria break down nitrates, nitrites, and ammonia, and liberate nitrogen, so that their activity leads to an excess of free nitrogen in the sea. On the other hand, bacteria are met with in the sea which are able to fix free nitrogen. On two occasions Knudsen found a great excess of nitrogen present in bottom water from the North Atlantic, a fact which he referred to putrefactive influences. The rapidity with which the atmospheric gases are diffused in sea-water is not yet known, but in pure fresh water the process is very slow. Probably the process of diffusion of gases in the sea is hastened by the constant stream of sinking particles, the shells and skeletons of the minute planktonic organisms, which carry down with them small quantities of gases. There are also convection currents, due to the unequal distribution of temperature, and these doubtless play an important part.

In the Eastern Mediterranean the deep water contains only from two-thirds to three-quarters of the amount of oxygen which should be present in water of its temperature. This deficiency is undoubtedly due to the utilisation of the oxygen by marine animals. It may be mentioned that the earliest analyses of the deeper waters of the Mediterranean gave such a low percentage of oxygen that it was concluded no animal life could exist. That animal life is found in the deepest Mediterranean waters has been proved by later expeditions, so that these earliest analyses must have been incorrect.

Nevertheless, there are sea areas in which the water does not contain sufficient oxygen to support fish or other animal life. These are, for the most part, seas in which there is some hindrance to the free circulation of the water.

As examples we find certain Norwegian fiords, the Black and Caspian Seas, and to a lesser extent certain deep areas of the Baltic.

Russian scientists have shown that animal life is not present, or indeed possible, at the greatest depths in the Black and Caspian Seas. In the Black Sea sulphuretted hydrogen is met with in sea-water at depths of 100 fathoms, whereas in the Caspian it is the lack of oxygen which is responsible for the absence of life in the lower layers. In the Caspian the greatest depth at which life was found was 218 fathoms, where a species of worm (Oligochæta) was met with. In certain Norwegian fiords—*e.g.*, Mofiord—there is no circulation between the waters of the fiord and those of the open sea, and consequently the lower layers are so deficient in oxygen as to be unable to support life. At the depths of 5½ fathoms there are 7·5 c.c. of oxygen per mille, at 27 fathoms only 0·86 c.c.

The *Challenger* results show that oxygen is found in excess in the surface layers of water in high southern latitudes, a phenomenon attributable to the preponderance of vegetable life in the plankton. Below 50 fathoms a diminution of oxygen becomes noticeable, and this becomes greater with the depth until at 800 fathoms oxygen is at its minimum. There is also a remarkable deficit of oxygen in the bottom waters of the North Pacific between 40° and 35° N. Lat. and 150° and 180° W. Long.

The estimation of *carbonic acid* in sea-water is a much more difficult matter. According to recent investigations, such as those of Fox, it would appear that the earlier troubles were due to the fact that it is difficult to get all the carbonic acid out of sea-water which is slightly alkaline.

The earlier analyses gave very different percentages of

CO_2 for the same water. Fox's recent work is based on the fact that the success in extricating gases dissolved in waters depends very largely on the maintenance of the evacuated space; the gases must be pumped away continually from the surface of the liquid as soon as evolved.

The alkalinity of sea-water varies, increasing in the neighbourhood of alkaline bottom sediments and where there is an appreciable mixture of land water, decreasing where there is a utilisation of carbonates by marine organisms. Certain marine sediments contain calcium and magnesium carbonates, and when there is an excess of free CO_2 these are dissolved, rendering the sea-water more alkaline. Water derived from the land might be expected to reduce the alkalinity of sea-water by dilution. But land water itself, especially "hard" water, is alkaline. An increase in alkalinity, though slight, has been determined off the west coast of Greenland, and this is attributed to the influence of water derived from the land. In Gullmar Fiord, Sweden, the water near the surface should have, according to the salinity, an alkalinity of 18·97; the alkalinity actually determined was 22·76. At 55 fathoms the alkalinity calculated from salinity (26·38) and that determined by analysis (26·37) approximate very closely. In the surface waters the difference is attributable to the influence of land water. Observations made in the Baltic under the auspices of the International Council also show how strong the influence of land water is in increasing alkalinity.

A decrease due to the activity of marine organisms is probably of no great significance. Sir John Murray estimated that one square mile of sea-water to a depth of 100 fathoms contains in the bodies of planktonic organisms 16 tons of calcium carbonate. Reduced to 1,000 c.c. (1 litre), the amount of carbonate of calcium is only 0·0255 milligram, which would give an alkalinity of 0·01 milligram. The amount of calcium carbonate in the skeletons and shells of marine planktonic organisms must be renewed twenty times

over before the results could exercise any effect appreciable to analysis.

The solubility of carbonic acid in water is directly dependent on the temperature.

The following table gives the coefficients of absorption for sea-water of salinity 35·19 per mille at different temperatures, compared with that of pure water :

	0° C.	5° C.	10° C.	15° C.	20° C.	25° C.	30° C.
Salt water (after Krogh) ...	1·41	1·17	0·99	0·85	0·74	0·65	0·57
Pure water (after Bohr and Bock)	1·71	1·19	1·19	1·02	0·88	0·76	0·67

The differences in the coefficients of absorption of carbonic acid decrease with a higher temperature, and at 30° C. are about one-third as large as at 0° C. From the above it follows that warm seas contain less carbonic acid than cold.

The chief source of oceanic carbonic acid is the atmosphere. There must, however, have been carbonic acid originally in sea-water. One source of carbonic acid is, according to Dittmar, the ocean bottom, especially where through submarine eruptions large quantities of gas are discharged. Sources of oceanic origin for carbonic acid have not yet been found, a condition probably due to the difficulty of collecting, preserving, and analysing suitable water samples. The bottom layers of waters in the great oceans are under a pressure of several hundred atmospheres, and consequently carbonic acid would be taken into solution in a liquid condition. Carbonic acid liquefies at 15° C. under pressure of 52 atmospheres, at 10° C. with pressure of 46, at 5° C. with 40, and at 0° C. under pressure of 35 atmospheres, and the critical point for pressure is at 73 atmospheres—that is, at depths of 400 fathoms. Below this depth carbonic acid is not met with in the gaseous condition.

An increase of carbonic acid due to the respiration of marine organisms is hardly perceptible, except in rare cases, where enclosed areas are responsible. As an example Gullmar Fiord in Bohuslan (Sweden) may be given. The effect of

variation in the solution of atmospheric gases in sea-water has been studied by Fraulein Lovén. Algæ in darkness can absorb all the oxygen present, and are able to live in oxygen-free water for sixty to seventy hours. Cod and Whiting kept in an aquarium for six hours reduced the oxygen from 5·18 c.c. to 0·19 c.c. (in 18½ litres), and increased the carbonic acid from 39·56 c.c. to 44·17 c.c. At this stage they died.

Smaller fish can endure a reduction of oxygen to 0·8 c.c., and will survive if afterwards they are placed in normal sea-water. Broadly speaking, in the presence of sunlight zoo-plankton increases the carbonic acid in sea-water, while the phytoplankton lessens it.

The chief cause of variation in the amount of carbonic acid in the sea is the atmosphere. Estimates have been made of the total amount of carbonic acid present in the sea and in the atmosphere respectively, and it is calculated that the former is twenty-seven times as great as the latter. There is almost certainly an exchange of carbonic acid between the sea and the air, dependent on the vapour tension of the carbonic acid in the sea and air respectively to one another. It has been calculated that the enormous pollution of the atmosphere produced by the burning of coal (780 million metric tons were consumed in 1901) is more than absorbed by the sea, which therefore acts as a regulator of carbonic acid in the atmosphere. The vapour tension of the carbonic acid in the air is less over the oceans and their coasts than over the land.

When a comparison is made of the volume of carbonic acid in sea-water, and when the variations are referred to their probable causes, it is found there are three—*Salinity, Temperature*, and the *Plankton*.

The International investigations show clearly that the amount of carbonic acid present is directly dependent on the salinity.

VARIATIONS OF CARBONIC ACID AND SALINITY.

	Salinity (per Mille)	Carbonic Acid (c c.).	Temperature.
Gulf of Bothnia	3·22 to 4·69	17·2 to 23·6	4·1 to 13·7
Northern Baltic	6·85	34·2	7·0
Belt. Fehmarn	12·03	35·24	0·7
Neustadt Bay	14·15	37·0	1·6
Skager-Rack	28·42 to 33·57	45·15 to 48·17	1·0 to 3·2
South of Iceland	35·0	49·0	—
Gulf of Naples	38·3	52·2	—
Eastern Mediterranean ...	39·0	53·04	26·7

At higher temperatures the amount of carbonic acid in solution is lessened.

Sea-Water as a Food Solution for Plants.

Since phytoplankton is found in the open ocean remote from any land, it follows that sea-water contains all the elements necessary for plant life. Generally speaking, the open oceans are less rich in plankton than coastal waters; again, tropical seas are poorer than colder waters, and this is directly dependent on the amount of vegetable food in the ocean. Incidentally marine animals, such as fish, are directly dependent ultimately on the plants in the sea, since this is their only source of organic nutriment. The colder seas of temperate regions contain not only fish in extraordinary shoals, such as the herring and cod, but also marine animals of the largest size, such as the right or true whales. Tropical seas fail in this respect.

Brandt has summarised the conditions under which plant and animal life flourish in the sea. Certain elements are absolutely indispensable for marine plants: these are carbon, oxygen, hydrogen, nitrogen, sulphur, phosphorus, calcium, potassium, magnesium, iron, and silicon. If one of these elements be absent plant life is impossible.

The amount of growth of the vegetable plankton is determined by the minimum quantity present of any one of

the above indispensable food substances. Conditions of life in the sea generally are far more uniform than on land. The enormous variations in moisture which land plants and animals have to contend with can be left out of consideration when dealing with the conditions of existence of marine organisms. The soil, which plays such an important part in the growth, distribution, and development of land flora, can be practically left out of account in dealing with marine plants. The range of temperature on land varies from 65° C. in Tibet to −66·6° C. in Siberia—that is, a range of 130°. In the open sea, on the contrary, the range is only 33·8°, from −2·8° to 31° C. It is highly significant that marine organisms are never exposed to lower temperatures than −2·8° C., since at that temperature the sea becomes covered with ice, which protects the lower layers of water from a further diminution of temperature, even when the temperature of the air sinks much lower.

In spite of the remarkable uniformity of temperature in the sea (when considered from a biological standpoint), there is a great difference in the species of organisms met with in cold and warm regions. And this difference extends to the abundance in which these organisms are met with. If the wealth of vegetable life in the sea were dependent only on sunlight, we should expect to find the tropical seas, like the tropical lands, with an abundance of vegetation. The fact that the production of organic from inorganic substances takes place by the aid of chlorophyll more rapidly in strong sunlight and at high temperatures would lead us to expect this. But the growth of plants is dependent still more on the presence of the food substances in solution in sea-water. If a single one of the indispensable elements be present in small quantities, then the production of the vegetable plankton is scanty. All marine plants depend for their nourishment on the water in which they live, and not on the soil or bottom of the sea, in this respect affording a marked contrast to land plants. This is true not only for floating algæ and diatoms, but also for bottom-living algæ (seaweeds) as well. The food substances

of all marine plants are therefore present in solution in sea-water, and those plants flourish according to the quantity of that indispensable food substance which is present in minimum amount. The question now arises, Which of the indispensable elements is present in minimum quantity in sea-water? The most important elements for prolific growth are phosphorus and nitrogen. Silica is apparently present at times in such small quantities as to come under consideration with respect to the growth and increase of certain planktonic plants which require large quantities of silica for their shells—*e.g.*, diatoms. After giving due consideration to the various elements, there seems, according to Brandt, to be no doubt that *nitrogen* is present in sea-water in such minute quantities as to be the controlling factor in the development of marine plants. In carp cultivation, which is especially developed on the Continent of Europe, those ponds which are provided with abundant nitrogen (in the form of manure) are found to be much more productive of carp flesh per unit of surface than similar ponds not so provided with dung. In the case of fresh-water lakes, a determination of nitrates by means of the diphenylamine-sulphuric acid reaction shows that those lakes which are rich in nitrogen are precisely those which have the most abundant plankton. Since all nitrogen compounds are easily soluble, we should expect the sea to be very rich in nitrogen on account of the waste of nitrogenous material from the land, but as a matter of fact sea-water is remarkably poor in nitrogen compounds.

This deficiency of nitrogen in the sea can be attributed to the presence of denitrifying bacteria. In nature the abundance and presence of nitrogen compounds is correlated with the activities of nitrogen bacteria.

These latter are of two kinds—Nitrifying bacteria, which oxidise ammonia, producing nitrous and nitric acids; and denitrifying bacteria, which reduce nitrogen compounds, liberating free nitrogen. If it had not been for the activity of these denitrifying bacteria the waters of the ocean would

long since have been poisoned by excess of nitrates derived from the land. For the details of the investigations into the activities of these bacteria the original papers should be consulted.

Determinations of the ammonia, nitrites, and nitrates in surface water have been made. The Baltic and North Seas analyses in 1904 gave on the average, for the Baltic, nitrogen (as ammonia) 0·061 plus (as nitrites and nitrates) 0·134 = 0·195 milligram per litre; for the North Sea (as ammonia) 0·058 plus (as nitrites and nitrates) 0·152 = 0·210 milligram per litre. For warmer seas investigations have been made by Natterer, who failed to find nitrates either in the surface or deeper waters of the Mediterranean and Red Seas. Nitrites were found in quite small quantities in the deeper layers, on the surface in traces only (0·008 to 0·011 milligram per litre). In the form of ammonia, nitrogen was present on the average in 0·060 milligram per litre, so that warm seas apparently contain only one-third of the amount of nitrogen found in cooler waters of Northern Europe. The warmer seas are therefore believed to have nitrogen present in minimum amount, and consequently they are poor in plankton.

The "law of the minimum" above referred to applies to other elements besides nitrogen, and it is quite possible that some other essential food substance for plants, such as phosphorus, is really that which regulates the amount of plankton. Older determinations of phosphoric acid in sea-water are unreliable, since they were not made on recently-collected and properly-filtered samples. The death and decay of planktonic organisms produces calcium phosphate, so that unless the water is promptly filtered and analysed phosphorus appears in excess.

Here again the International investigations afford fresh results for consideration. Baltic and North Sea water is found to contain more phosphoric acid than nitrogen, but, even so, less than 1 milligram per litre. There is a yearly fluctuation in February and May from 0·14 to 0·25 milligram phosphoric

acid per litre, and in autumn considerably more, up to 1·46 milligrams per litre.

The same reasoning applies to silica, which is present in North European waters in from 0·65 to 1·45 milligrams per litre. There is a yearly periodicity, the minimum being in May and the maximum in February. This appears to be connected with the enormous growth of diatoms, silica-utilising organisms, which takes place between February and May.

Salinity.

An important subject for the oceanographer's consideration is the distribution, both horizontal and vertical, of the salinity of the waters of the sea, and for the vertical distribution it is necessary carefully to collect samples of water from varying depths. For this purpose many kinds of "water-bottles" have been devised, one of which, that of Pettersson-Nansen, is described here. The bottle is really a device for securing a sample of sea-water from any required depth, the sample being insulated in such a manner as to prevent any change in the temperature of the water during the time the bottle is being hauled inboard.

The bottle, which consists essentially of three concentric cylinders of a non-conductive medium (vulcanite), is lowered to the required depth when open, and closed by means of a messenger sent down the wire. In the upper lids of the bottle a deep-sea thermometer is fixed. Water is thus collected from the depth to which the bottle has been lowered, and this instrument is found satisfactory up to depths of 500 to 800 metres (273 to 382 fathoms). The temperature is checked by means of a delicate deep-sea thermometer of the Richter type, which is attached to one arm of the Pettersson-Nansen apparatus outside the bottle, and which is inverted by the same messenger which closes the bottle (not shown in the figure). If the bottle be used for depths of 400 fathoms and over, then, although the isolation of the enclosed water sample

may be satisfactory, there is nevertheless a change of temperature, due to the diminution of pressure on the enclosed water. This change of temperature is inappreciable in shallow water. But in greater depths the release of pressure which takes place during the hauling in lowers the temperature of the enclosed



FIG. 16.—THE PETTERSSON-NANSEN WATER-BOTTLE.

sample. For that reason the thermometer inside the water-bottle is not relied upon absolutely, but is compared with the outside reading given by the inverted Richter thermometer.

Surface Salinities.

The Atlantic Ocean has the highest surface salinities. These attain in the North Atlantic a maximum of over 37 per mille from the Canary Islands to 55° W. Long., and on both sides of the Tropic of Cancer from 17° to 30° N. Lat. the

coastal waters of Morocco have a salinity a little less than 35·5, the Gulf Stream to 40° N. Lat. over 36 per thousand.

The salinity declines in the region of the equatorial calms. On the tropical coasts of West Africa it is under 34·5 per mille, but in regions reached by the South Equatorial Current it is over 35·5.

In contrast to the North, the *South Atlantic* has its maximum salinity not far from the American coast, between 12° and 21° S. Lat., and from the neighbourhood of the coast to nearly 10° W. Long. On the other hand, the salinity in the South Atlantic decreases rapidly to the southward, so that south of 40° S. Lat. a salinity of over 35 is only met with south of the Cape of Good Hope and in the southern extensions of the Brazilian Current.

The Caribbean Sea has a salinity of between 35·5 and 36, except in the immediate vicinity of the coasts, where it is somewhat less, but as we proceed north and west the salinity increases; near Jamaica it is 36, in the Gulf of Mexico 36·9, except on the north and west coasts, where the influence of the Mississippi makes itself felt.

The North Atlantic waters have been investigated in detail in recent years by the International Commission, and here, as elsewhere, the connection between ocean currents and salinity is very noticeable. The so-called Gulf Stream or Atlantic Drift water between the Faroes and Scotland has a salinity between 35 and 35·3, and branches of this drift can be traced as far as and beyond the North Cape. On the opposite coast of Greenland the Polar Current has water of under 33 per mille, and in regions where melting ice is met with this may sink to 30. Kara Sea has a salinity of about 30, with a maximum of 31·3, while the coastal waters of North Siberia sink to 22 or even 21 per thousand. A branch of the Atlantic Drift extends up into Baffin's Bay, where salinity of 33 has been met with.

CHAPTER IV

WAVES

WHEN the surface of the sea is disturbed, waves are produced. The chief characteristic of such wave-motion is that while the waves pass over the surface at considerable speed, the water itself simply rises and falls with a slight to-and-fro motion of a rhythmic character. The theory of wave-motion establishes by mathematical calculation a relation between the length of the wave (the distance between consecutive crests), its velocity, and the depth of the water, and thus affords an explanation of the difference in behaviour of waves in the deep sea and the same waves when they reach shallow water.

There is a simple relation common to all types of wave-motion where waves follow one another in trains, either in the air, ether, or water, and it is expressed by the formula

$$L = VT,$$

where L is the length of the wave, V its velocity, and T the period of oscillation of the particles which are effected by successive waves.

It must be borne in mind that in a typical deep-sea wave it is not the mass of water which is being bodily transferred, but the energy.

Let QR be a straight line under which the circle with radius OQ rolls. The length QR being made equal to a semi-circumference, the rolling circle will have made a semi-revolution during its motion from Q to R; and if QR and the semi-circumference QR' are each divided into the same number of equal parts, then as the circle rolls the points with corresponding numbers come into contact successively. Now take a point

P on the radius *OR′* of the rolling circle; then this tracing-point as the circle rolls will trace a curve, known as a "trochoid" (*Pc2h2* in the diagram), which is the theoretical wave profile from hollow to crest. To determine a point on the trochoid, as the rolling circle advances a point on its circumference (say 3) comes into contact with the corresponding number on the line *QR*. The centres of the circles must at that instant (*S*) be vertically below the point of contact (3), and the angle through which the circular disc and the tracing arm *OP* have both turned is given by *QO3*. But the angle *POc* on the original position of the circles = *QO3*; consequently through *S* draw *Sc2* parallel to *Oc*, and make *Sc2* = *Oc*; then *c2* is a point on the trochoid.

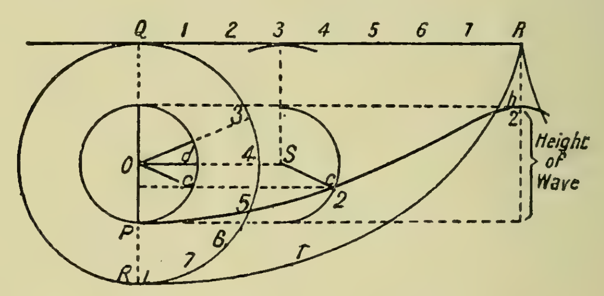


Fig. 17.—A Trochoid Wave.

The tracing-arm *OP* may, for wave-motion, have any value not greater than the radius of the rolling circle *OQ*.

If *OP* = *OQ* the tracing-point lies on the circumference of the rolling circle, and the curve traced is a cycloid and corresponds to a wave on the point of breaking.

The curve *R′ TR* shows a cycloid. The crest is a sharp line or ridge (at *R*), while the hollow is a very flat curve.

All deep-sea waves have this trochoid profile.

The *length* of the wave is its measurement from crest to crest (*QR* in the figure is half the wave-length); the *height* of the wave is reckoned from hollow to crest; and the *period* is the time its crest or hollow takes in traversing a distance equal to its own length.

Consider the motion of the particles of water. Every particle revolves with uniform speed in a circular orbit, and completes a revolution during the period in which the wave advances through its own length. Assume the circles represent the position at successive eighths of a whole revolution. Let *PPP* be particles on the upper surface, then the wave of the radii of the orbits is *OP*, *OP*, etc. Assume one-eighth of a revolution to be accomplished, then the points *P* occupy the position *R*, and *RRR* will be a trochoid identical in form with *PPP*, but with its crest and hollow farther to the left. The motion of the particles in the direction of the advance is limited by the diameter of their orbits, and they move to and fro about the centres of the orbits.

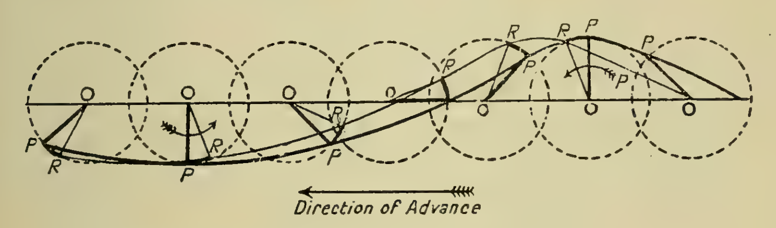


FIG. 18.—THE ADVANCE OF A WAVE.

The diagram shows how, on the trochoidal theory of wave-motion, the wave-form advances very rapidly, while the individual particles have little or no advance.

It will be noticed that on the ridge of the wave the particles move in the same direction as the advancing wave, in the trough of the wave in the contrary direction.

When a cork is dropped overboard from a ship it does not travel away on the wave on which it falls, but simply sways backwards and forwards, following the line of motion of the particle *P* in the above diagram.

The disturbance caused by the passage of a wave must extend for some distance below the surface, until at length at great depths the disturbance will have ceased.

The trochoidal theory expresses the law of decrease, and

enables the whole internal structure of such a wave to be illustrated.

At the surface the radius of the circle described by a revolving particle is equal to half the wave-height. Under-surface particles describe similar circles, but with ever-diminishing radii. It is beyond the scope of this work to give detailed proof of the laws regulating their movements. Broadly speaking the heights of the subsurface trochoids diminish in a geometrical progression, while the depth increases in arithmetical progression, and the following rule is approximately correct.

The orbits and velocities of the particles of water are diminished by *one-half* for each additional depth below the mid-height of the surface wave equal to *one-ninth* of a wave-length—*i.e.:*

Depth in fractions of a wave-length below the mid-height of the surface wave ...	0	$\frac{1}{9}$	$\frac{2}{9}$	$\frac{3}{9}$	$\frac{4}{9}$	$\frac{5}{9}$	$\frac{8}{9}$,	etc.
Proportionate velocities and diameters ...	1	$\frac{1}{2}$	$\frac{1}{4}$	$\frac{1}{8}$	$\frac{1}{16}$	$\frac{1}{32}$	$\frac{1}{256}$,	etc.

Waves of 90 metres length and 3 metres height are not uncommon with strong winds in the open ocean.

At 10 metres depth the height of the subsurface trochoid would be 1·5 metres; at 20 metres depth 0·75 metres; at 50 metres only 9 centimetres; in 100 metres not quite 3 millimetres —that is, hardly perceptible.

An ocean storm-wave 600 feet long and 40 feet high from hollow to crest would have at a depth of 200 feet a subsurface trochoid with a height of 5 feet; at 400 feet ($\frac{6}{9}$ of the length) a trochoid of 7 or 8 inches only.

This rule and these examples are sufficient for practical purposes.

"Very often the motions of these originally vertical columns of particles have been compared to those occurring in a corn-field, where the stalks sway to and fro and a wave-form travels across the top of the growing corn. But while there are points of resemblance between the two cases, there is also this important difference—the corn-stalks are of constant

length, whereas the originally vertical columns become elongated in the neighbourhood of the wave crests, and shortened near the wave hollows " (White).

The Tides.

The term " tide " is given to the periodic rise and fall of the sea-surface. Naturally this rise and fall is more obvious on the coast-line, and is of such a nature that the period between the heights of two successive rises or falls is approximately half a day.

The highest water-level attained by a given tide is called high-water, the lowest low-water; the rise of the tide from the lowest to the highest position is called the flood and the fall from the highest to the lowest position the ebb. The perpendicular distance between the water-levels at high and low water is the range of the tide.

If observations on the rise and fall of the tide be made for a period of not less than fourteen days it will be seen that there are variations both in the time at which high-water is attained and the height attained by the tide at its maximum. Every fourteen days the tide at high-water attains a maximum and minimum height. The former is a spring-tide, the latter a neap-tide.

The duration of a " flood "—that is, the time between the lowest water of a tide and the highest water of the succeeding tide—is not exactly six hours, so that the interval between corresponding tides in successive days is on the average 24 hours 40 minutes; and this circumstance, as well as the fortnightly interval between successive spring-tides, is associated with the movement of the moon. The duration of a tide is almost exactly half a lunar day, while the period between successive spring-tides is equivalent to half the time taken by the moon to revolve round the earth.

As a consequence at every place or port it is noticed that the time of high-water seems to follow the moon's meridional

passage by a certain interval of time. This interval varies greatly for different ports, but is fairly constant for any given port, and the time of high-water at any port on the day of new or full moon is known as the vulgar establishment of the port.

The establishment of a port is the interval between the time of high-water and the preceding meridional passage of the moon at new or full moon. Exact observation proves that the interval between the moon's meridional passage and the following high-water is not always the same, but alters with the age of the moon. On the days of the four principal phases of the moon it is the same, but from new moon to the first quarter, and from full moon to the last quarter, high-water occurs earlier, and in the other two quarters of the moon later, than would be the case if the time-interval were invariable.

There are other minor variations in the rise of the tide. In many places the tides are during half the year higher in the forenoon than in the afternoon, the reverse being true for the other half-year.

The character of individual tides is subject to great irregularities. In bays, gulfs, estuaries, and other enclosed sea areas, the time occupied by the flood-tide is much smaller than the ebb, and this is more noticeable at springs than at neaps. The peculiarities of the tides depend to a great extent on the locality where the observations are made. On small oceanic islands the rise is very small, seldom exceeding a metre. In other localities apparently only one tide is noticeable. In enclosed seas such as the Mediterranean and Baltic the tides are so slight as to be only perceptible to careful investigation. In narrow straits, bays, and estuaries, the highest tides are attained. In certain extreme cases tidal waves are formed. In long, narrow channels, such as estuaries, the flood-tide runs for less than an hour and a half, while the ebb-tide runs over eleven hours. Such a sudden rush of water is accompanied by a phenomenon known as a "bore," which is occasionally a tidal wave of considerable height and velocity. In narrow channels of this description

the rise of the tide occasionally attains remarkable dimensions. The best and most-quoted instance is that of the Bay of Fundy, where at Cape Sable the rise is only 2·6 metres, but in the innermost reaches of Mines Basin spring-tides rise 15 to 16 metres.

In the British Isles the greatest rise of the tide is in the Bristol Channel, where at Clevedon Pier on April 8, 1879, the ascertained rise was 15·9 metres.

Tide-Recorders or Water-Gauges.

To elucidate the laws governing tidal movements it is indispensable that careful records should be made of the rise and fall of the tide in as many selected localities as possible. The best form of instrument is the self-registering tide gauge, of which there are several types. The principle is a simple one. A float is connected by means of a bronze wire with a self-recording pen or pencil which writes on a vertical cylinder of paper. This paper revolves by means of clock-work, and thus a curve is traced on the surface of the paper. This curve is the tide for the selected locality. An inspection of a few automatic tidal records gives one a good idea of the irregularity of the tides.

Tidal Theories.

The first general explanation of the phenomena of the tides was given by Newton, though the connection between the movements of the sun and moon and the rise and fall of the tides had long previously been noted. Newton's theory of gravitation was applied to account for the tides. He supposed the ocean to cover the whole earth, and to assume at each instant a figure of equilibrium under the combined gravitation influence of the earth, moon, and sun.

There are four main tidal theories :

1. The equilibrium theory (Newton).
2. The dynamical theory of Laplace.
3. The canal theory of Airy.
4. The stationary wave theory of Harris.

The Equilibrium Theory.—Let us consider the influence of the sun and moon on the earth's surface.

For simplicity, take the sun alone in the first place. Let S be the sun, and E the earth. If the attraction of the sun were not present the earth would move in a straight line from E to X; but as a matter of fact the earth actually moves

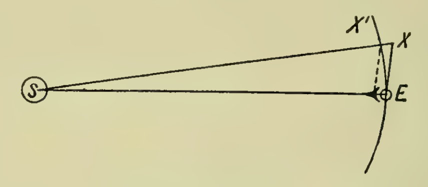


FIG. 19A.—EQUILIBRIUM THEORY OF THE TIDES.

from E to X'. The attraction of the sun at any point is inversely proportional to the square of its distance from the point, so that particles on the side of the earth nearest the sun are more attracted than those on the far side. Assume now that the surface of the earth is entirely covered with water, then it follows that this universal ocean would take an ellipsoidal form. The waters would be heaped up most at the

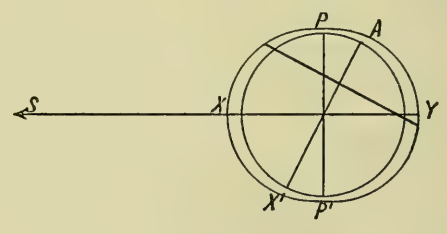


FIG. 19B.—EQUILIBRIUM THEORY OF THE TIDES.

points X and Y, and would be flattest at PP' (AX' being the earth's axis).

Every point on this imaginary universal ocean would rotate once in twenty-four hours round the axis AX', and since the sun's gravitational attraction on the line XY remains constant, it follows that once in every twenty-four hours every point in the ocean comes under the influence of the nearer protuberance

(X), and twelve hours later under the further protuberance (Y)—that is to say, has two high-waters daily and twice daily passes through a low-water position (along the line PP').

A similar gravitational attraction is exercised by the moon, but in this case it is the moon which moves around the earth; or, strictly speaking, both bodies move around their common centre of gravity. Owing to the difference in size between the moon and earth, this common centre of gravity actually lies within the earth, at about three-quarters of the radius from the earth's centre.

This mutual rotation around a common centre of gravity produces two forces—

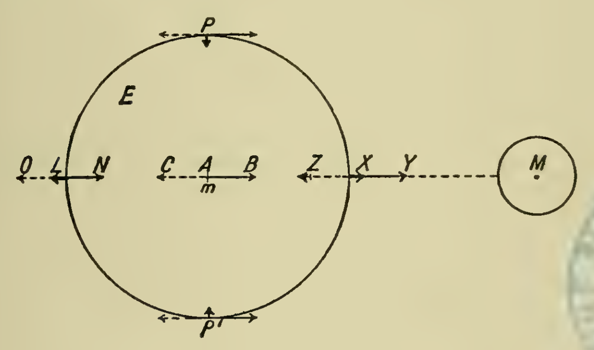


FIG. 19C.—EQUILIBRIUM THEORY OF THE TIDES.

(1) A centrifugal force which is similar at all points of the earth's surface.

(2) An attractive force by the moon on the earth (and, of course, by the earth on the moon).

The above figure shows the relative strength of the tide-producing force of the moon at different points at the earth's surface compared with the centrifugal force due to the earth's rotation.

At m, the middle point of the earth, the attraction of the moon is equal to the centrifugal force, and $AB=AC$. At X, which is nearer to the moon than A, the attraction of the moon is greater than the centrifugal force, and XY is greater than XZ. At L the attraction of the moon is less than at A, and

LN is less than *LO*. The differences between the earth's centrifugal force and the attraction of the moon at the points *X* and *L* on the earth's surface are shown by the arrows. At *X* movable portions of the earth (sea-water) are pulled towards the moon; at *L* a residuum of force pulls the sea-water outwards and upwards in contrary direction to that at *X*.

At *P* and *P′* a pair of forces are present, which result in a pull towards the earth's centre. Consequently, if we imagine the earth to be covered with a liquid, there must be a heaping up at *X* and *L* and a depression at *P* and *P′*.

George Darwin has prepared a diagram which shows the

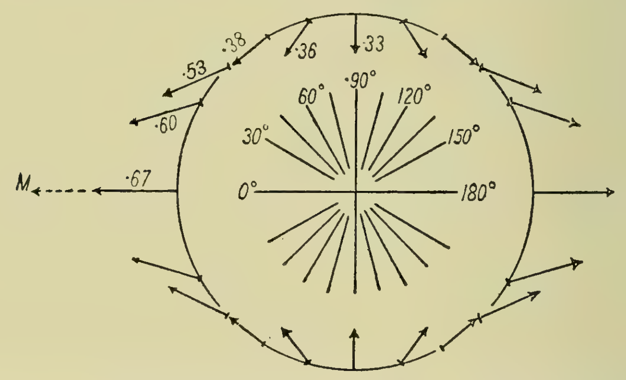


FIG. 19D.—DIRECTION AND STRENGTH OF THE TIDE-PRODUCING FORCES DUE TO THE MOON. (AFTER G. H. DARWIN.)

direction and relative strengths of these forces at various points on the earth's surface.

On the water surface it is only the horizontal components of the tide-producing force which are effective. The horizontal components of the tide-producing forces produce their effect of "pull" precisely at those two points where the line joining the tide-producing body (sun or moon) to the earth's centre cuts the earth's surface. Its maximum force is attained at a distance of 45° from these points.

The distribution of these forces on a planet whose surface was entirely water is shown on the accompanying figure.

The tide-producing force, be it of the sun or the moon,

causes the waters of the earth to assume an ellipsoidal form. The water rises and falls according to the attraction of these two bodies, and since the sun and moon appear perpendicular above a given point on the earth's surface at different times, it follows that each tide ellipsoid is at different places at different times. Each point on the ocean is acted upon by two forces, the sun and the moon, each tending to produce its own tide-ellipsoid. But since both the influence of the sun and the moon is felt simultaneously, it follows that the actual tide-ellipsoid present at any point is a combination of the tide-ellipsoid formed by the action of the sun added to that formed

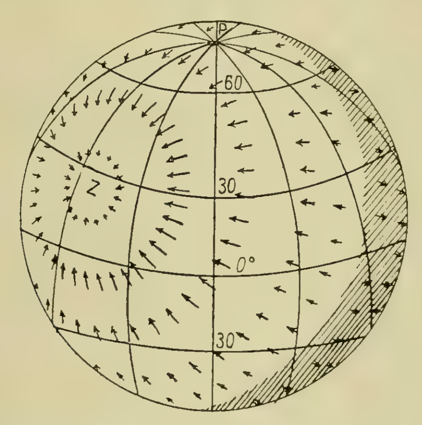


FIG. 19E.—DISTRIBUTION OF TIDE-PRODUCING FORCE ON THE EARTH'S SURFACE.

by the action of the moon. Since the positions of the sun and the moon only alter slowly, it follows that the resulting tide-ellipsoid only alters slowly. There are two extreme positions. One is when the earth, sun, and moon are all in the same straight line (full moon and new moon). Here the axes of the tide-ellipsoids produced by both sun and moon are in the same straight line and can be added together. This produces the high-tides known as *springs*, and the sun and moon are either in opposition or conjunction (Syzygy). The second extreme case occurs when the sun and moon are in quadrature—*i.e.*, at right angles to one another, the moon now being in the first or

last quarter. In this case the tide-ellipsoid produced by the moon has its maximum protuberance coincident with the maximum depression of the tide-ellipsoid produced by the sun. Consequently, the resulting height of the observed tide is a minimum and we get the period of *neap-tide*.

The Strength of the Tide-Producing Forces.

Let the mass of the earth = 1 and that of the moon = M. Then $M = 1/81\cdot45$. The attractive force of the moon at the earth's centre is proportional to M/r^2, where r is the distance between the centres of the earth and moon. At the point on the earth where the line joining the earth and moon's centres cuts the surface the attraction of the moon is somewhat greater, being proportional to $M/(r-r')^2$, where r' is the radius of the earth.

The difference between these two attractive forces is that which gives the "pull" on the water particles at the earth's surface and produces the protuberance at this point. This difference is—

$$\frac{M}{(r-r')^2} - \frac{M}{r^2} = \frac{M}{r^2}\left[\frac{1}{\left[1-\frac{r'}{r}\right]^2} - 1\right].$$

But $r : r' = 1 : 60\cdot34$

$$\therefore \qquad = \frac{M}{r^2}\left[1 + \frac{2r'}{r} + \ldots - 1\right].$$

which is for all practical purposes

$$= \frac{2Mr'}{r^3}.$$

The force with which the earth attracts a particle at its surface is $\frac{1}{r'^2}$, and the force which produces the tides is the fraction of this—

$$= \frac{2Mr'}{r^3} : \frac{1}{r'^2} = \frac{2Mr'^3}{r^3} = \frac{1}{8945000}$$

—that is, the tide-producing force of the moon is about one-nine-millionth of the force of gravity.

Supposing the moon's attractive force were not at work, then at a given point on the surface of the ocean the attraction of the earth would be $\frac{1}{r'^2}$.

Assuming the moon to act, then this pull is lessened, and to assume a position of equilibrium the water moves away from the earth to a distance h, so that it is now $r'+h$ away from the earth's centre. Gravity at this point is $\frac{1}{(r'+h)^2}$.

Consequently, the diminution is—

$$\frac{1}{r'^2} - \frac{1}{(r' + h)^2} = \frac{1}{r'^2}\left[1 - \frac{1}{\left[1 + \frac{h}{r'}\right]^2}\right].$$

Omitting infinitesimal calculations, this gives—

$$\frac{1}{r'^2} : \frac{2h}{r'}$$

—that is, $\frac{2h}{r'}$ of the total attraction of the earth, but the tide-producing force is $\frac{1}{8945000}$;

so that $$\frac{2h}{r'} = \frac{1}{8945000},$$

since $$r'=6370300\ M,$$
$$h=0{\cdot}356\ M,$$

and the height of the tide due to the moon is only 356 millimetres. A similar calculation for the sun shows that its attractive force produces a tide of 164 millimetres, so that the moon's attractive force is 2·171 times that of the sun, or, roughly, as 11 is to 5.

Lord Kelvin devised a method for the harmonic analysis of the tides. In this method the tide-wave, considered with reference to the time when it reaches a given point of the earth's surface and to its height at that point, is made up of the superposition of a series of waves of different amplitudes and

periods, arising from the different relative positions and varying distances from the earth of the disturbing bodies, the sun and moon, and of the variation of certain elements of their orbits. Of these waves, each of which has a typical analytical expression, the twenty-three following are the most important :

Two : The lunar monthly and solar annual (elliptic).
Two : The lunar fortnightly and solar semi-annual (declinational).
Four : The lunar and solar diurnal (declinational).
Two : The lunar and solar semi-diurnal.
Seven : The lunar and solar elliptic diurnal.
Four : The lunar and solar elliptic semi-diurnal.
Two : The lunar and solar declinational semi-diurnal.

The numerous calculations necessary in the harmonic analysis can be performed by a machine—the tidal predictor—invented by Lord Kelvin. This machine mechanically delineates the tidal curves from day to day, and, indeed, from instant to instant. There are four of these instruments in existence, belonging to the Governments of Great Britain, France, India, and the United States.

According to Airy, the equilibrium theory of tides of Newton is one of the most contemptible theories that was ever applied to explain a collection of important physical facts. It is entirely false in its principles, and entirely inapplicable in its results. It has, however, been of historical utility, since it has served to show that there are forces in Nature following laws which bear a not very distant relation to some of the most conspicuous phenomena of the tides. It has given an algebraic form to its results which coincides with those of more accurate theories. The greatest mathematicians and the most laborious observers have agreed equally in rejecting the foundation of this theory and comparing all their observations with its results.

The theory of Laplace assumes the earth to be covered with

water, and the depth of this water to be the same through the whole extent of any parallel of latitude. The motion of the water which forms the variable elevations of the tides at different parts of the earth must be conceived to be principally a horizontal oscillation, the water on both sides of the highest point at any time having run towards that point in order to raise the surface there, and consequently, since the highest point occupies different positions at different times, the water at any particular place runs sometimes in one direction and sometimes in another. Combining this with the general result of the equilibrium theory of the tides (semi-diurnal)—namely, that the water is equally raised at two opposite points—it follows that if a canal were traced through the water forming a great circle of the earth it would (in certain positions of the sun and moon) be divided into four parts, in two of which the water is running in one direction, and in the other two it is running in the opposite direction.

The mathematical exposition of Laplace's theory is given in detail by Airy.*

A marked advance both in theory and practice was registered by the canal theory of Airy. In it the motion of the tidal waters is supposed to be that of ordinary waves in canals. This theory does not apply to all places in the sea, and is therefore to that extent imperfect. Still, it does apply strictly in many cases, to rivers without exception; to arms of the sea where their breadth is smaller than their length and where the irregularities of the coast are not very remarkable; and it applies without sensible modification to other cases of open seas, where the whole may be conceived divided into parallel canals in which the circumstances are nearly similar.

As will be deduced from the preceding account of waves, a wave in continuous motion does not imply that the water is continuously moving in the same direction. It is only the motion of a shape. The motion of a wave has been explained by consideration of the oscillatory motion of the particles,

* "Waves and Tides," Sections 72-127.

When waves are short—*i.e.*, when the depth is great in comparison with the length of the wave, as in the case of ordinary waves in the open sea—the motion is not sensible except near the surface, where each particle moves uniformly in a circle.

In shallow water, where the length of the wave is great in proportion to the depth of the water, each particle moves in an ellipse.

In the tide-wave travelling along a channel the water is travelling forward with its greatest speed at the time of high-water or at the top of the wave. When the water is at its mean height its velocity is 0—that is, it is still water. When the water is at its greatest depression it is running backwards with its greatest velocity.

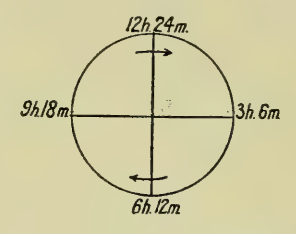


Fig. 20.—Motion of a Surface Particle in a Tidal Wave in Deep Water.

Consider the motion of a surface particle in a tidal wave in deep water. The periodicity is 12 hours 24 minutes. Let the wave move to the right. At the commencement of the motion we have high-water, at 3 hours 6 minutes it is mid-water, at 6 hours 12 minutes low-water, at 9 hours 18 minutes mid-water again, and at 12 hours 24 minutes again high-water.

From 0 hours to 6 hours 12 minutes the particle moves from its highest to its lowest level. This part of the vertical movement is the ebb of the tide; from 6 hours 12 minutes to 12 hours 24 minutes the particle moves from its lowest to its highest position—this is the flood-tide. The vertical movement is not felt as a stream, only the horizontal; and this in

the case of the figure is for the flood-tide from 3 hours 6 minutes before to 3 hours 6 minutes after high-water. On the contrary, the ebb runs so long as the particle lies under mid-water level—that is, from 3 hours 6 minutes before low-water to 3 hours 6 minutes after low-water. It is slack water at the moment the particle passes through the mid-water position.

This phenomenon in deep water appears quite different if one stands on the coast. Here the change in the direction of the current does not follow 3 hours 6 minutes after high or low water, but coincides with it.

This change in the tidal stream does not, however, take place everywhere at high and low water. On London Bridge the flood-stream continues to run even after the water has fallen 2 feet, as can easily be noted by direct observation.

Seamen know well that in the middle of the English Channel the flood runs three hours after high-water and the ebb three hours after low-water—that is, exactly according to the above theory. In the Pentland Firth, between Stroma and Swona, the stream changes exactly three hours after high and low water.

Our knowledge of the tides and tidal streams of the world is still very incomplete. There is a complete lack of tidal observations in the centres of the great oceans.

Only in the southern ocean is there a complete water-belt round which it is possible for the two tidal waves to travel. These are known as *primary waves*.

A primary wave sweeping round the southern ocean, passing in succession the southern coasts of Australia, Africa, and South America, may be assumed to give off secondary waves which pass up the three great oceans in a more or less northerly direction. These are *derived waves*, and from them arise the tides along the various coasts which they pass. Consider the Atlantic Ocean.

On this theory a derived wave passes up it. It is deflected and retarded by the continental coasts, as it passes from south

to north. A detailed consideration of these derived waves is impossible here,* but a brief account of the tides and tidal streams of the British Isles is given below.

The Tides of the British Isles.

The main tidal undulation from the Atlantic approaches the British Islands from a south-westerly direction, the line of its crest running north-west and south-east.

It makes high-water on the Atlantic coasts of the British Isles, on full and change days, at from 4½ o'clock to 6½ o'clock Greenwich mean time; it reaches Ushant a little before 4, the south-west of Ireland at 4.30, Scilly Islands at 4.50, the north-western extremity of Ireland at 5.30, and the outer Hebrides at 6.30, Greenwich mean time (Fig. 21).

The undulation is practically unobstructed in ocean depths, and here it does not appear to exceed 5 feet in height, and is probably much less.

When it reaches the continental shelf on which the British Isles are situated it becomes obstructed and its progress is retarded. Ultimately it divides into three main streams, one up the English Channel, one up the Irish Channel, and the third up the trough to the west of Ireland lying between the Scottish coast and Rockall, and extending northwards towards the Faroes.

The tidal undulation has a greater elevation at its south-east part than elsewhere, the height of the crest above the trough being about 10 feet at the south-west of Ireland and 19 feet at Ushant; and this peculiarity is preserved in its progress up the English, Bristol, and Irish Channels, the range of the tide being always greater on the right or south-eastern part of the advancing wave. This is reversed when the wave has rounded the north coast of Scotland; then the western part of the undulation is higher than the eastern.

There are three greater and three lesser maxima developed —viz.:

* See Harris, "Manual of the Tides."

Greater Maxima—

1. A crest of 37 feet from trough to summit in the St. Malo Bight.

2. A crest of 42 feet from trough to summit at Portishead.

3. A crest of 22 to 23 feet from trough to summit in the Wash.

Lesser Maxima—

1. A crest of 24 to 28 feet in the English Channel between Hastings and the Somme.

2. A crest of 27 to 28 feet in Liverpool, Morecambe Bay, and Solway Firth.

3. A crest of 12 feet at the entrance to the River Weser.

The three greater maxima occur almost simultaneously between 6.30 and 7.30 G.M.T., and the lesser maxima between 10.45 and 11.45 G.M.T. on full and change days.

The undulation causing high-water in the English Channel is from 15 to 16 feet in height on the English coast from Land's End to the Start, and from 19 to 23 feet on the French coast from Ushant to Île de Bas. It assumes a convex form as it moves up the Channel, moving more rapidly in the fairway than along the coasts.

On the French coast it is obstructed by the peninsula terminating in Cape La Hague, the water backing up and causing the tidal wave to reach a height of 37 feet at St. Malo.

On the English coast, after passing the Start, its height diminishes owing to the lateral movement into Lyme Bay, so that the height is only 9 feet at Portland and 7½ at the Needles, while at Cherbourg the undulation is about 18 feet high.

By this time the undulation has been transformed into a purely horizontal movement, the eastern part of the English Channel being a large basin with a comparatively narrow entrance between the Isle of Wight and Cape Barfleur. The tide fills this basin at a great rate. After passing the Isle of Wight and Cape La Hogue, the undulation increases considerably in height, caused by the stream meeting that coming

from the North Sea, with a resulting backing up of the water.

There are minor peculiarities, such as prolonged high-water at Havre (for three hours), or prolonged low-water at Portland (for four hours, locally known as the Gulder), but these are due to the bottling up of the water in a comparatively large basin and its difficulty of escaping through a narrow passage.

In the Irish Sea the tidal wave as it approaches develops two heads to its convex front, one for the Bristol Channel and the other for the Irish Sea.

The first wave reaches Lundy at 5.30 G.M.T. on full and change days, and passes up the Bristol Channel, being to a certain extent reflected from one side to another, so gradually adding to the height of the crest, which reaches 42 feet at Portishead at springs.

The second wave reaches Carnsore and the Smalls Lighthouse at 6 hours 25 minutes G.M.T. on full and change days, with a crest of 9 feet at springs at Carnsore, and 21 feet at the Smalls.

The Irish Sea being open to the northward, this same tidal undulation enters through the North Channel between Rathlin Island and Cantyre, also at 6 hours 25 minutes, thus making it high-water simultaneously at each opening of the Irish Sea, while at the same time it is low-water, or nearly so, in the Dee, Mersey, Ribble, Morecambe Bay, and Solway Firth.

The southern undulation, running up St. George's Channel, causes high-water all along the west coasts of Wales, England, and Scotland, as far as the Mull of Galloway.

To the westward of the British Isles, in the deep-water channel between them and Rockall, the tidal undulation assumes the shape of waves caused by a steamer travelling at great speed, with bow and lateral waves. These lateral waves on the east side become eventually almost parallel to the coast, so that it is high-water on the west coasts of Ireland

and Scotland for a distance of over 400 miles between 4.30 and 6.30 p.m. G.M.T. on full and change days.

The tidal wave approaches the Orkneys and Shetlands, owing to retardation of the southern side of the wave in shallow water, almost in a parallel direction to the coast. The undulation has a height of 10 feet at the Orkneys and 5 to 6 feet at the Shetlands at springs.

The North Sea is open to tidal influence at both entrances: on the south through the Straits of Dover, and on the north to the undulation coming round the north of Scotland. This undulation has its south-western portion considerably retarded when it reaches the Orkneys and Shetlands. The tidal wave bends round the northern end of the British Isles, and reaches the coast of Norway at 10 o'clock G.M.T. on full and change days, with a height of under 5 feet, having travelled across the intervening area at a rate of 120 miles per hour. At the time of high-water at Dover (11 o'clock) the same tidal undulation, travelling round north of the British Isles, has reached the south-western corner of Norway.

The tidal undulation takes seven hours to travel up the English Channel, about 300 miles, while its northern offset only takes two and a half hours to the Faroes, 500 miles, and about five hours to the northern end of the Shetlands, a distance of 600 miles.

The tidal wave in the Channel is directed towards the Schelde mainly, but part of it is deflected towards the coast of Holland, acquiring a rotatory motion round the Brown Ridges.

The Norwegian wave appears to be reflected back and to be superimposed on the undulation passing through the Orkney and Shetland Channels, so that it moves towards the east coast of Great Britain in a line almost parallel to the coast, and from Aberdeen to Cromer in a wave from 14 to 16 feet high, except in certain estuaries, such as the Humber and the Wash, where, owing to the formation of the coast, it is forced to a height of from 20 to 23 feet. The southern part of the

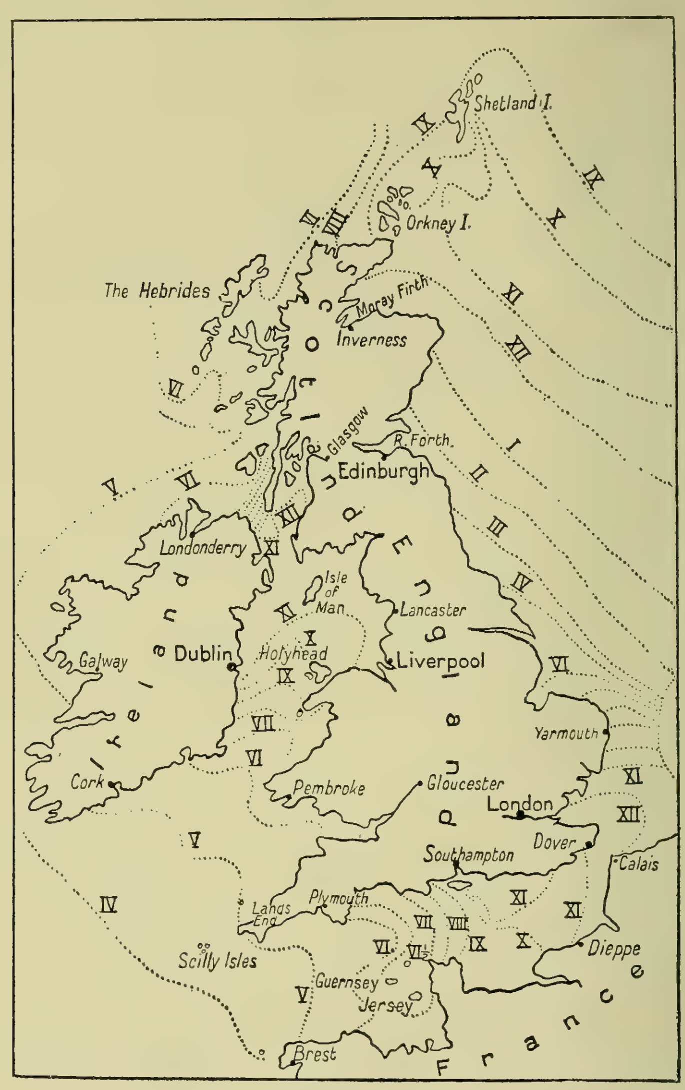


FIG. 21.—THE TIDES OF THE BRITISH ISLES.

Norwegian undulation travels to the coasts of Germany and Denmark, and, becoming superimposed on the wave from the Channel, makes a higher undulation of 12 feet in the Jade, Weser, and Elbe.

The Tidal Streams.

So long as the tidal undulation travels in great depths it is a simple wave, but when it meets with obstructions it is translated into a wave of horizontal force—*i.e.*, a tidal stream, as distinct from a wave, is produced.

Even off the banks to the south-west of the British Isles, such as the Jones, Scot, and Nymphe Banks, ripples and overfalls are observed even in the finest weather. These are due to the tide.

These phenomena are universally met with. Where submarine elevations are met with, rising suddenly from great oceanic depths (2,000 fathoms), tide ripples are seen even when such elevations are 800 fathoms below the surface.

The details of the force and direction of the tidal streams round the British Isles are too complicated to be dealt with here.*

There is, however, one phenomenon which must be noticed briefly. Over certain areas the whole body of water oscillates backwards and forwards with the regularity of a pendulum having a stroke of about 6¼ hours, the total oscillation being from about 10 to 20 miles backwards and forwards.

These oscillations occur simultaneously, or nearly so, over areas widely removed from each other, and appear to coincide almost exactly with the rise and fall of the tide in a given spot.

Fifteen such oscillations are described and figured in the Admiralty manual on the tidal streams of the British Isles.

One may be quoted as an example. In the southern part of the Irish Sea there is an oscillating area bounded on the south by a line joining Carnsore Point and the Smalls Lighthouse, on the north by a line joining St. John's Point (Ireland), the Point of Ayre (Isle of Man), and the north end of Walney Island, on the east by the west coast of England

* See "The Tides and Tidal Streams of the British Isles," etc. First edition, 1909. London: Hydrographic Office, Admiralty.

and Wales, and on the west by the east coast of Ireland. In this area the whole body of water is moving southwards while the tide is falling at Liverpool north-west lightship, and northwards while the tide is rising there.

There is another oscillating area in the north part of the Irish Sea contiguous to the above. The waters in these two areas move towards each other while the tide is rising at the Liverpool north-west ship (or Dover), and away from each other with the falling tide there. Summing up, it may be said that "in order to supply the water necessary for the tidal wave as it advances from ocean depths toward shallow banks, horizontal movements are set up, which oscillate backwards and forwards over certain areas; and these horizontal movements, when obstructed, either by meeting a coast-line or by meeting each other, pile up the waters to a height far exceeding the height of the normal tidal undulation propagated in the ocean, and so produce the abnormal rises and falls which are so noted in the Bristol Channel, at Liverpool, and among the Channel Islands."

Ocean Waves.

Ocean waves are caused by the wind. The term "swell" is applied to waves not produced by the wind in the locality where such waves are met with, but caused by storms at a distance. Occasionally it is possible for an observer on board ship to distinguish "sea"—*i.e.*, waves produced by wind locally—and "swell," waves produced by wind at a distance.

Measurements of the dimension of oceanic waves are by no means easy, as the sources of error are hard to eliminate. Most estimates of oceanic wave-heights recorded by seafarers are too high. In the figure the height given by the observer is *cd*, whereas the height of the wave is really only *ab*. The observer on a rolling or pitching ship is the victim of an optical illusion.

Waves vary in different localities, according to the velocity and direction of the wind. The longest wave recorded is one of 2,600 feet length and 23 seconds period by the French

Admiral Mottez in the Atlantic Ocean a little north of the Equator in 28° W. Long.

Although there is a definite relationship between the period, velocity, and length of a wave, there is none between these and the height. The longest waves are usually met with in the South Pacific, where their lengths vary from 600 to 1,000 feet and their periods from 11 to 14 seconds. Waves of from 500 to 600 feet in length are sometimes met in the Atlantic, but the usual lengths are from 160 to 320 feet, and the periods from 6 to 8 seconds. As to the heights of waves there is much conflicting evidence in the records. Dumont D'Urville has recorded a wave 100 feet high in 1837 off the Cape of Good Hope. This was an estimate, not a measurement, and although many seafarers will agree with D'Urville, the estimate is

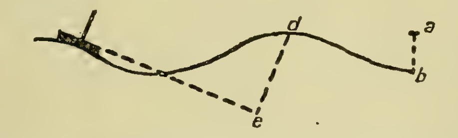


FIG. 22.—ERRONEOUS ESTIMATION OF HEIGHT OF WAVE ON PITCHING VESSEL.

probably too high. French marine officers measured many waves according to instructions given by Arago. The highest measured were in February, 1841, near the Azores, when from 42 to 50 feet was recorded. In the enclosed seas the height of waves is much less. Probably in the North Sea waves never exceed 31 feet in height, with periodicity of 9 seconds and wave-length 147 feet (as maxima).

There is considerable speculation amongst fishermen and seafaring men as to which, if any, of a group of waves is the highest. This idea was known to the ancient Greeks, who wrote of groups of three waves as being the highest in a seaway. Vaughan Cornish describes groups of three waves as being higher than the rest in stormy weather in the North Atlantic, and he claims to have followed them with the eye for more than a mile when standing on the steamer's bridge.

Seafaring men generally say that in stormy weather the fourth or fifth wave is the highest, and that this wave is followed by one or two of less height, which gives a favourable opportunity of putting the ship about should that be necessary.

When waves are first formed by the wind they are short and steep, but if the wind continue to blow in the same direction for some time their length and height increase, but the periodicity decreases until a balance of forces is produced. In calm weather the first hint of a breeze is given by the darkening of the sea surface. The growth of waves from the smallest capillary waves to the highest waves has been treated mathematically by Airy* and others. When waves have once been formed the wind has greatest effect on their crest, which it tends to drive faster than the main body of the wave, and so causes the wave to break. In deep water waves have no motion of translation, but on reaching shallow water their troughs are retarded, so that they break and rush forward with considerable force; these are the "breakers" of the coast.

The growth of waves is hindered by foreign bodies in the water, such as mud or sand in suspension, ice, seaweed, oil, heavy rain, hail, or sleet. Particles of ice, or sand, or mud in suspension increase the viscosity and so hinder wave-formation. The gigantic seaweeds of high southern latitudes (*Macrocystis pyrifera*), which flourish on rocky coasts, exercise a remarkable effect in stilling the waves, so much so that in Kingston (South Australia) an open bay has been made a safe anchorage.

* "Waves and Tides."

CHAPTER V

Ocean Currents

The commonest method of detecting the existence of ocean currents is by ship's reckoning. The master of every ship is supposed at midday to determine his position by means of astronomical calculations based on the observed height of the sun. He is also in a position to calculate his course and the distance travelled since the preceding observation of yesterday. The difference between the positions determined by astronomical observation and by course and log gives an

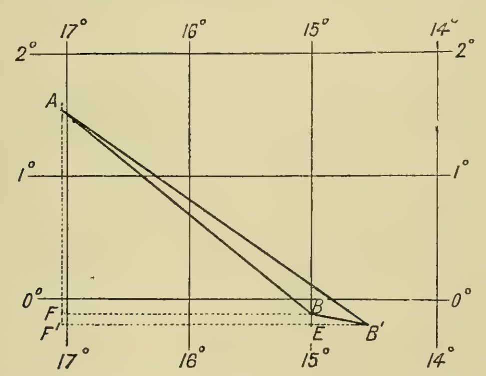


Fig. 23.—Surface Currents: Estimation by Ship's Reckoning.

indication of the ocean currents in the locality traversed. As an example, suppose a vessel at noon of a certain date is at the point *A* in the diagram (Fig. 23). A course is steered in a south-easterly direction, and as a result of twenty-four hours' steaming 180 miles are logged, so that the position of the steamer is *B'*.

An astronomical observation shows that the true position of the ship is, however, *B*.

It follows that the steamer on its voyage from *A* in a direction towards *B'* has met with some force which has pushed it out of its direction and shortened its course. This force is the ocean current of the locality, and the displacement of the steamer is represented by the line *B'B*. This can be measured, both in magnitude and direction. Let us suppose that it is 26 sea miles and in direction west by north. This gives us the velocity and direction of the current for twenty-four hours. Near the Equator the estimation is simple, but in higher latitudes other calculations are necessary.

In observations of this kind there are many sources of error, so that one isolated record is not of much value.

Current Meters.

(A) Surface.

(B) Deep-sea.

Surface Meters.

Modern determination of ocean currents depends on the use of various instruments; the principal types only are described here.

In the *Challenger* expedition floating buoys were used, and to these were attached by means of a line, two frames of sail-cloth arranged at right angles and kept immersed by means of a lead weight. When the apparatus was not in use the frames could be folded together. The actual determination of surface currents by a ship anchored at sea is attended with considerable difficulty.* If one anchor alone be used, the ship sways to and fro to a great extent, thus hindering the observations. Three anchors are found to be necessary to give a satisfactory result, and it will be easily understood that to anchor a ship in the open sea for a sufficiently long period to enable current observations to be made is an expensive process, and one not unattended with danger.

* See Pillsbury, U.S. Coast Survey Report for 1890, Appendix X., pp. 516-537. Washington, 1891.

Deep-Sea Current Meters.

The International investigations into the North and neighbouring seas have led to the introduction of several new and interesting experiments in deep-sea research. Amongst the apparatus tried is the deep-sea current-meter of Ekman (see

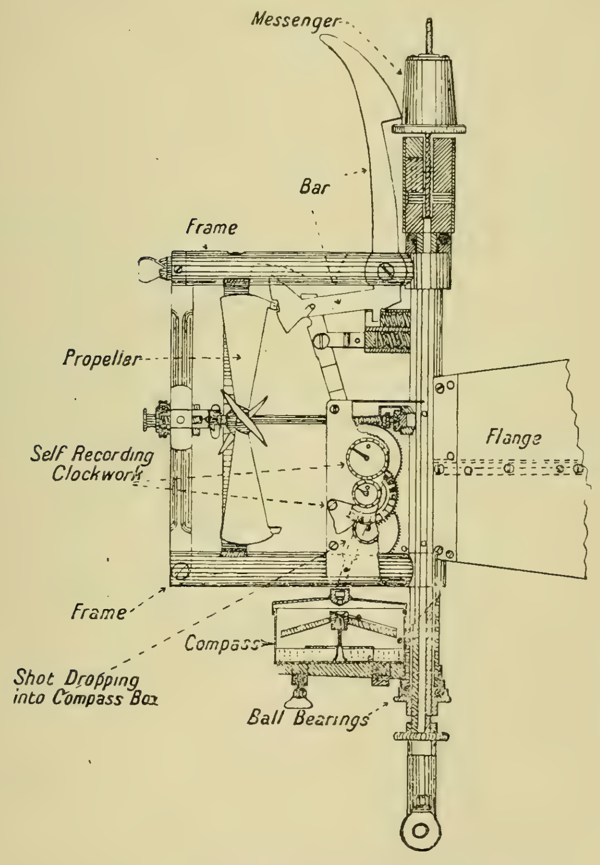


FIG. 24.—THE EKMAN DEEP-SEA CURRENT METER.

Fig. 24). The apparatus is attached to a large "sail" or flange, which sets itself in the direction of the current—*i.e.*, in the line of least resistance. A frame working on ball-bearings is attached to a line which can be lowered to any required distance. Inside the frame is a four-bladed propeller

which rotates by the action of the current. The rotation is registered and recorded, and gives a measure of the velocity of the current. The propeller is made fast by means of a hook which can be released by the messenger sent down the wire. The number of revolutions of the propeller being recorded, the velocity of the stream or current can be calculated from a prepared table. The direction of the current is ascertained by means of an apparatus attached to the revolving arm which leads off from the propeller. This apparatus consists of a rotating wheel divided into compartments, each of which contains a separate shot. Every thirty revolutions of the propeller liberates a shot, which falls into a box containing a compass needle which is suitably grooved. Below the needle is a box divided into thirty-six compartments, each of which therefore corresponds to 10° of the compass. The shot rolls down the compass into one of these compartments. From the distribution of the shot in the various compartments the average direction of the current can be ascertained. Ekman's current-meter can be used in great depths, but owing to its complicated construction it requires careful handling. Owing to friction, the meter will not register currents of less velocity than 3 centimetres per second. In actual practice the instrument is rather difficult to use, since it is necessary to moor the boat or ship very securely, to prevent moving or swinging by surface currents.

Floating and drifting bodies in the ocean give a valuable indication of the direction and velocity of ocean currents. When the floating objects are fully submerged they give an indication of the ocean currents only; when a part of the object projects from the water, the influence of the wind has to be taken into calculation.

The plankton serves, in a way, as an indicator of ocean currents, but the extent of our knowledge of the distribution of planktonic organisms is not sufficiently wide to justify the extensive use of this method at present. The researches of the International Commission have, however, given us much

information in the case of the waters of the North European Seas.* The "weed" of the Sargasso Sea is an example of natural drift bodies. The large pods of a mimosa (*Entada gigalobium*) which is indigenous to the Antilles are frequently found to have drifted across the Atlantic to the shores of the Azores, Canary Islands, Ireland, Iceland, and even the coasts of Norway, North Spitsbergen, and Nova Zembla. Timber from the forests of Northern Siberia has been found to drift across the Arctic Sea to Northern Iceland and Greenland. Formerly, when their shores were more wooded than now,

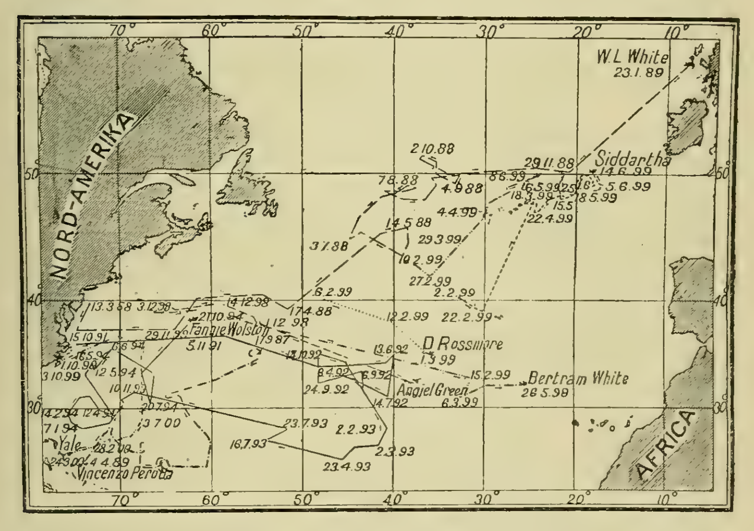


FIG. 25.—DRIFTING WRECKS IN THE NORTH ATLANTIC. (KRÜMMEL.)

West Indian mahogany and St. Lawrence firs and pines drifted across the Atlantic as far as the North Sea coasts of Europe.

Another source of important information as to ocean currents is furnished by icebergs, of which one-fifth of the bulk usually projects from the water. Derelict ships have also afforded information.

* See Johnstone, "Conditions of Life in the Sea," p. 151 *et seq.* Cambridge University Press, 1908.

In the much-frequented waters of the North Atlantic Ocean there are records of the drift of derelict vessels affording an interesting side-light on the ocean currents of that area.

In the appended figure are shown the courses of several of these vessels under the influence of the Gulf Stream drift. American coasting vessels laden with wood, when they become derelict or unmanageable, often drift for long periods, sinking deeper in the ocean as the wood which forms their cargo absorbs water and becomes heavier. The most famous case is that of the schooner *Fanny Wolston,* timber-laden, which drifted about for the best part of three years (October 15, 1891, to October 21, 1894). During 1,100 days this wreck travelled a distance of not less than 8,000 sea miles, in its last year a great loop in a clock-wise direction off the entrance to the Gulf of Mexico.

A second notable instance is that of the American schooner *W. L. White,* which became a derelict off the coast of Baltimore on March 13, 1888. Two of its three masts remained, so that not only was it subject to the influence of the Gulf Stream, but also of the prevailing south-west wind. It travelled speedily to the neighbourhood of Newfoundland, where it was sighted on May 30, 1888. At this time the masts were gone and the main deck under water, so that subsequently it followed closely the drift of the Gulf Stream. Being in the steamer route of the North Atlantic, it was frequently seen and recorded by passing vessels. It was finally salved near the Hebrides on January 23, 1889.

In a drift of 317 days' duration the *W. L. White* travelled nearly 5,200 sea miles. A somewhat similar course was followed by the barque *Siddartha.*

The steamer *Rossmore* and the schooners *Angiel Green* and *Bertram White* drifted to the southward of the Azores. A course between that of the *Siddartha* and the *W. L. White* was followed by an unknown barque.

The *Yale* and the *Vincenzo Perotta* followed different courses from their commencement in the neighbourhood of

the West Indian Islands. Broadly speaking, they followed the Gulf Stream drift, though in the latter portion of its career the *Yale* drifted into the Labrador Current. In December, 1887, a giant raft, consisting of 27,000 beams of timber, broke adrift on a journey from Fundy Bay to New York when on the Nantucket Bank in 41° 16′ N. Lat. and 70° 6′ W. Long. This

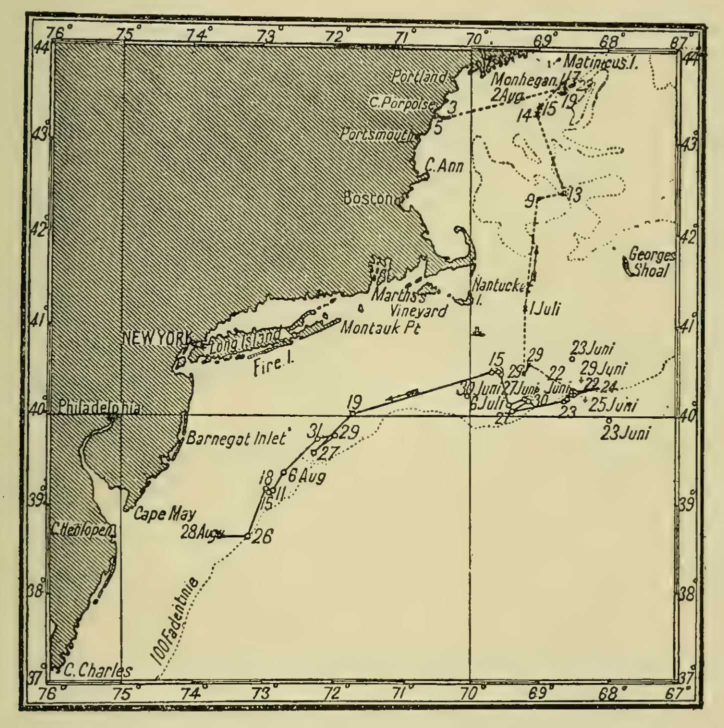


FIG. 26.—THE DRIFT OF THE DERELICT SCHOONER "FRED TAYLOR." (AFTER KRÜMMEL.)

timber drifted to the eastward, and in February, 1888, was observed in thick masses in 65° W., in March in 60° W., and, somewhat more scattered, off the Azores (30° W.) in July, and in September in widely-scattered fragments north of Madeira. In the summer of 1892 a small reed and wood "island" had drifted over 1,000 sea miles from the South American coast.

A curious instance is that of the American schooner *Fred*

Taylor. This vessel was run down by the German steamer *Trave* on June 22, 1892, in 40° 19′ N. Lat. and 68° 33′ W. Long., and cut into two parts. The two parts drifted in an entirely different direction, and at first sight it seems inexplicable why they should have behaved in this extraordinary fashion. The stern drifted to the north and stranded on August 7 on the United States coast near Cape Porpoise; the bow went to the south-west and sank on August 28 off the entrance to Delaware Bay. The cause of this difference in the drift is undoubtedly to be attributed to the influence of the wind. The bow was deep in the water and not much influenced by the wind; the stern, on the contrary, was high out of the water, and consequently moved under wind pressure. Except for two occasions (June 27 to 30 and July 27 to 29), when there was a gale from the south-west, the bow drifted solely under the influence of the cold Labrador Current. The influence of this current is also noticeable in the case of the stern, which, in spite of the prevailing south-west wind, drifted, not to the north-east, but more to the north.

A case of different drift of drift-bottles set free at the same time has also been noted. Ten drift-bottles were set free north of St. Paul's Island (1° 44′ N. Lat., 27° 16′ W. Long.), of which two were subsequently found—one after 377 days, on the east coast of Nicaragua (Central America); the other 196 days after, not far from Sierra Leone, on the African coast. The difference in the drift here is not attributable to the influence of wind, but to the fact that the bottles were set free close to the junction of the west-going Equatorial Current and the east-going Guinea Stream. Drifting wrecks or derelict vessels are easily recognisable, and since they are a danger to navigation their presence is usually recorded in the ship's log-book, together with the locality and date of observation. They are then reported to the Admiralty or Hydrographic Office of the reporting vessel, and, in the case of the North Atlantic, arrangements had been made, prior to the outbreak of war in 1914, for their destruction.

Drift-bottles are also used for determination of ocean currents. These bottles, which are suitably weighted with sand so as to float just immersed, contain a stamped postcard asking the finder to return them, with the locality and date of finding. Floating bottles have long been used by seafarers in distress to give information as to the accident which has befallen them and their position. Bottles have been used for current determination for over 100 years, the first summary on a large scale being that by the French hydrographer Daussy in 1839 in the North Atlantic. Sir John Ross criticised what he called the "bottle fallacy," and of course, like all other scientific experiments, these weighted drift-bottles are liable to give erroneous or inaccurate or incomplete information. The chief difficulty is that even when the points of origin and termination of the bottle's journey are accurately known, it by no means follows that the bottle has drifted in a straight line from one place to the other. Again, if any portion of the bottle projects from the water it comes under the influence of the wind, and is therefore a measure, not of the ocean current alone, but of the ocean current plus the wind.

The Prince of Monaco distributed 1,675 weighted bottles in the North Atlantic in 1885-1888, and of these 227 were recovered—that is, from one-seventh to one-eighth of the original number. In limited areas, such as the Irish Sea, the number recovered may be considerably larger. In 1894-1895 the Lancashire Fisheries Committee distributed 1,045 bottles, mainly on the Liverpool-Douglas line, but also on the Liverpool-Holyhead and Liverpool-Greenock lines. Of these, 440, or 42 per cent., were recovered. Again in 1898, of 101 bottles distributed, 41, or 40·5 per cent., were recovered. Subject to certain limitations, the drift-bottle evidence is of some value in the determination of ocean currents. Another indirect method of determining the existence of ocean currents is by means of the *thermometer and aerometer*. Bodies of water which move as ocean currents have marked physical features, and in particular the temperature and salinity vary

but little over wide limits. Consequently it is possible to determine the existence of such a current—*e.g.*, the Gulf Stream or Labrador Current—by thermometrical and aerometrical observations alone.

Theories of Ocean Currents.

Early theories of the cause of ocean currents were for the most part fantastical. One idea was that ocean currents were attributable to *cosmic* influences. Anciently it was thought that all ocean currents had a westerly trend, and this was attributed to the rotation of the earth and the gravitational attraction of the moon.

Other theories attribute ocean currents to differences of water temperature, to an interaction of the *vis inertiæ* of the water and the rotation of the earth, or finally to the prevailing winds.

An attractive theory is that which attributes ocean currents to differences in specific gravity of sea-water caused by differences in temperature and salinity. Amongst modern investigators this theory is supported by Nansen. That it is not a new idea is, however, shown by the fact that it was held in the time of Columbus by Leonardo da Vinci.

Seafaring men, as a rule, believe that currents are mainly caused by wind, and though some influence is doubtless exercised by the wind, it will not by itself account for all ocean currents. Some physicists doubt the power of the wind to set in motion large volumes of sea-water.

Alexander von Humboldt (1816) gave a clear account of the possible factors causing ocean currents. These were, briefly, the temperature and salinity of the water, the periodical melting of Polar ice, variable evaporation at different places on the ocean surface, and, finally, differences in atmospheric pressure.

Sometimes these causes work in conjunction, sometimes in opposition. Modern ideas take into consideration many

possible factors as influencing ocean currents. The main causes are divisible into two groups—(1) Those within the water—*e.g.*, differences in density, temperature, and salinity, which are in part due to geographical causes, such as variations in sunlight, evaporation, rain-fall, or melting ice; and (2) those outside the water—*e.g.*, wind and its causes, *i.e.*, variation in atmospheric pressure.

Among the secondary influences is *friction*, which doubtless plays a part in all movements of sea-water; the rotation of the earth, and the geographical configuration of the coast-line.

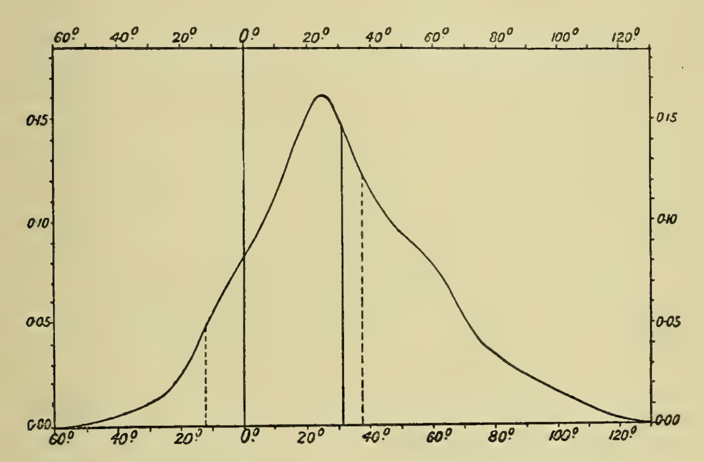


FIG. 27.—DEVIATION OF OCEAN CURRENTS DUE TO EARTH'S ROTATION. (KRÜMMEL.)

THE INFLUENCE OF THE EARTH'S ROTATION.

All surface currents, whether of air or water, are affected by the earth's rotation, and in such a manner that in the Northern Hemisphere they are deflected to the right and in the Southern Hemisphere to the left. The deflection varies with the latitude, and is at its maximum at the Poles, and at the Equator non-existent.

The influence of the rotation of the earth on ocean currents has been determined by direct observation. Since the waters of the sea and ocean are influenced by tidal streams, winds,

and other causes, it is not easy to determine the influence of the earth's rotation in causing a deviation of ocean currents. In the case of atmospheric currents the same difficulties are not present, or if present, then not felt to the same degree, so that the deviation of atmospheric currents caused by the earth's rotation is easy to determine.

The most suitable localities for investigation are those free from tidal streams and strong ocean currents, such as the Baltic and Mediterranean. Here the only influence causing currents is the wind, and since the direction of the wind can be observed, we can tell in what direction the current should flow if it is caused by wind alone. Investigations into the influence of the earth's rotation have been made both in the Baltic and the Mediterranean Seas, and the result of one such series of investigations is recorded briefly here. Records were kept for 294 days on the Adlergrund Lightship in the Baltic. Every two hours the direction of the wind, its strength (on the Beaufort scale), the direction and strength of the current in the sea at 5 metres depth, were recorded. Tidal streams were absent. The wind caused a current, and this was readily observed up to the depth of 5 metres. Occasionally the wind changed too rapidly to enable satisfactory observations to be made, so that only 226 days gave suitable records. On many days, however, the wind was too feeble (below 3 on Beaufort's scale) to cause a sufficiently strongly-marked current to be noted, so that finally the records of 131 days were selected for analysis. On these days the wind exceeded 3 on the Beaufort scale, and the stream over 3·7 miles, in the twenty-four hours. The angle was measured between the actual direction of the current and the wind, and this gives the deviation due to the rotation of the earth, all other possible causes being excluded. There is found to be a marked deviation to the right, and, as will be seen on reference to the figure (Fig. 27), the maximum deviation is 25° to the right.

Influence of the Coast.

Marked deviations in the courses of ocean currents are produced by the obstructive influence of the coasts of the various continents and islands.

Variations in Density.

Variations in the density of the sea-water are due either to differences in salinity or temperature, or both combined. Actually variations in salinity are more commonly the cause of differences of density in sea-water. Only in the greater oceanic depths, where the salinity of large volumes of sea-water is practically constant, is there any marked variation in density due to temperature changes. But even here salinity changes are of greater importance in producing alterations in density, and consequently setting up ocean currents.

From depths of 2,000 metres downwards the temperature and salinity in the whole of the Pacific and Indian Oceans (except in the highest latitudes) and in the south-west of the South Atlantic are very similar, whereas in the North Atlantic the water at similar depths has higher salinity and temperature. Although our knowledge of oceanic salinities at these depths is very defective, we can assume that in the North Atlantic it is 35 per mille, in the Southern Atlantic and Indian Oceans 34·65 per mille, and in the Pacific 34·60 per mille. The bottom waters of the North Atlantic are heavier than those of the adjacent oceanic areas, and consequently there should be a bottom current flowing southwards. This current, if it in fact exists, has not yet been observed.

The Polar Origin of Abyssal Waters.

At depths of 2,000 fathoms and over the waters of all oceans are very cold, and but a little above the freezing-point of fresh water. Even in tropical regions the bottom temperatures are only 1° C. or a little over, and Murray says that the

ooze dredged from the ocean floor in the tropics is so cold that it cannot be handled without discomfort. The lowest deep-sea temperatures are found in the oceans of the Southern Hemisphere, and, broadly speaking, higher temperatures are recorded as one recedes from Antarctic regions.

One theory of the cause of such low deep-sea temperatures is that they are due to submerged Polar currents, and that there is, in fact, a vertical circulation of the following kind:

The cold surface waters of the Polar regions sink to the bottom on account of their greater density. This water layer moves towards the Equator, increasing in temperature from 2 to 3° C. on the way. In tropical regions the heated surface waters move towards the Poles. The facts which support the theory of a bottom current from the Polar to tropical regions may be grouped under six headings:

1. All oceanic depths greater than 2,000 metres are filled with water of the same density (with small variations) and a temperature between 0° and 3° C. This points to a vertical circulation. In this enormous volume of deep-sea water there are only minute variations of temperature, and these would be still smaller but for the fact that near the freezing-point there are but slight variations in the density of sea-water for each degree of change in the temperature.

2. The lowest bottom temperatures are found where the great oceans have both wide and deep connection with Polar areas, and the bottom temperatures increase the farther one recedes from the Poles and the nearer one approaches the Equator. The depths of the North Polar seas are shut off from neighbouring depths by slight ridges, so that the bulk of the abyssal waters of the great oceans comes from the Antarctic, and it follows that the southern oceans have the lowest bottom temperatures. On the western side of the South Atlantic there is a tongue of water of only 0·3° C., which reaches to 30° S. Lat. (the Argentine Deep). This water is separated by a comparatively narrow mixed layer from water of 2·8° C., which is the average temperature of Atlantic water of that

depth. The uniform bottom temperature of the Pacific Ocean, which averages 1·6° C., also supports the idea of a bottom Polar current.

3. The colder bottom water of Polar origin is not found in sea and ocean areas shut off from Polar regions by submarine ridges. In such cases the bottom temperature is practically the same as that found at the apex of the ridge.

4. In the North Atlantic there are strong surface currents, which are sharply marked off from deeper water by a sudden increase of temperature of from 4° to 5° C. This shows that the bottom layers of water are uninfluenced by strong surface currents, that there is little or no mixture of currents, and that the surface currents pursue their way unaffected by, and unaffecting, the movements of the deeper oceanic waters.

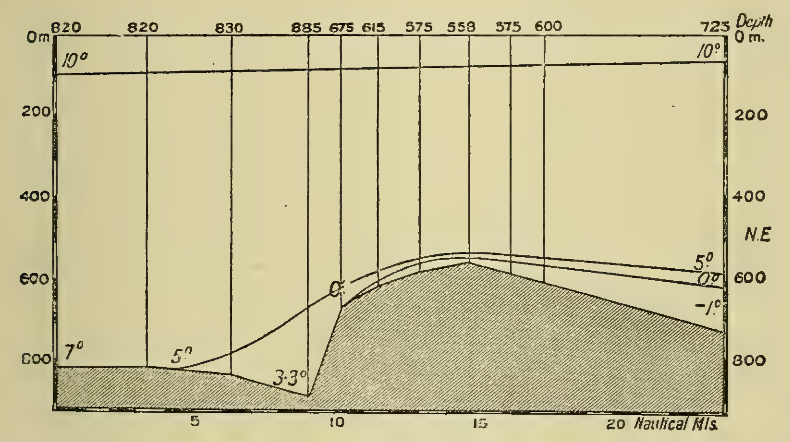


Fig. 28.—Isotherms indicating Bottom Current over the Wyville-Thomson Ridge.

5. As a matter of fact, cold Polar water sinks, and this has been practically demonstrated by the celebrated explorer Amundsen in the neighbourhood of Spitsbergen. The depth of the Norwegian Sea is filled with Atlantic water of high salinity (the so-called Gulf Stream drift); this water, from its nitrogen contents, must have been previously on the surface, and has sunk owing to its having been cooled.

6. In some instances a bottom current has been observed, notably by Tizard in 1882 on the Wyville-Thomson ridge, between Scotland and the Faroes. This ridge separates a cold and warm area.

The warm Atlantic surface water flows north, and the cold water found on the northern side of the ridge is this water which has cooled and sunk and then flowed down to the ridge. The result is that there is cold water on both sides of the ridge, but on the north of the ridge the decrease downwards is much greater than on the south. The form of the isothermal lines in the figure is that of a volume of water flowing over a weir (from right to left in the illustration). Not only are there theoretical reasons for this cold current, but as a fact the current on the ridge is sufficiently strong to keep it clear of sediment.

Currents in Narrow Waters.

As a rule currents in narrow waters connecting oceans and seas are due to differences in sea-water density. In high latitudes, where the rainfall is high and evaporation relatively low, fresh water plays a part, causing a raising of the water-level. The converse holds good in lower latitudes. In the absence of wind and tide—*i.e.*, on quiet days at neap-tides—two distinct currents are observed in narrow straits, the upper moving to the region of water of higher density; that is, in the Straits of Gibraltar and Bab el Mandeb from the ocean to the sea, and conversely in the Bosporus and in Cabot Strait. The rotation of the earth causes a deflection of the stream to the right in the Northern Hemisphere, so that in the Straits of Gibraltar it is bent to the Moroccan coast.

In most straits, especially those which open to the ocean, there are strong tides, and these tend to obscure the currents. Observations for the determination of a current should extend for a period of thirteen hours, to cover a complete tide.

Melting Ice.

According to Pettersson, melting ice plays an important part in causing ocean currents, not only in the displacement of large water masses in the Southern Hemisphere, but also in the formation of important ocean currents, of which the East Greenland Current may be taken as a type.*

Atmospheric Pressure and Ocean Currents.

Atmospheric pressure is an important factor in the causation of ocean currents, and it works in two ways—partly by local variations in pressure and partly through wind. The ocean is really a gigantic water barometer. When the barometer rises over a given water area, it is equivalent to an extra pressure on the water surface, which consequently sinks. Pressure gradients are consequently formed as the result of a variation of atmospheric pressure.

During the monsoon period gradients are caused in the transitional period from high to low atmospheric pressure. The extra pressure on the water when the barometer is high causes a flow of water to areas of lower atmospheric pressure. With a low barometer off the Shetlands and a high one off the Continental coast, the North Sea water is forced in two or three days to the north. When the barometer falls over the Baltic and rises over the northern part of the North Sea, water is forced in through the Belt into the Baltic. Knudsen says that the strength of the current at the entrance to the Baltic is directly proportional to the variations in atmospheric pressure in the North and Baltic Seas. If v be the velocity of the stream, then

$$v = \frac{p - e}{a} + c\,(B - B'),$$

when p is the rainfall, e the evaporation, a the section of the exit (0·8 square kilometre), c a constant (estimated by Knudsen

* *Geographical Journal*, vol. xxiv., p. 285, and vol. xxv., p. 279.

to be 22·1), B' the original similar atmospheric pressure in the North and Baltic Seas, and B the new pressure over the North Sea.

Knudsen thinks that the influence of the atmospheric pressure on the currents in the Belt is much more marked than the wind.

Wind and Ocean Currents.

The influence of the wind has long been disputed as a cause of ocean currents, though navigators have always inclined to the theory that wind is an important factor. Franklin thought the trade winds were the cause of the tropical westerly current met with where they prevail, and, indeed, he thought that the wind was the principal cause of ocean currents. Rennell divided ocean currents into two groups—*drift currents,* directly attributable to prevailing wind; and *stream currents,* due to the stemming or damming of drift currents by the coast or other currents. Stream currents can flow against the prevailing winds. Most British geographers adopt Rennell's classification. Findlay says, however, that the wind can only influence quite superficial layers of water, at the most to a depth of 5 or 6 fathoms.

Ocean Currents.

The Atlantic Ocean.

The currents of the Atlantic Ocean have been observed in more detail than either of the other oceans.

It is convenient to consider the Atlantic currents under five headings—viz.:

1. The equatorial currents.
2. The Florida Current (the so-called Gulf Stream).
3. The South Atlantic currents.
4. Deep-sea currents.

5. Currents in the land-locked Atlantic seas.

1. The Equatorial Currents.—There are two main equatorial currents—

(*a*) The *Northern* Equatorial Current, corresponding to the north-east trade wind.

(*b*) The *Southern* Equatorial Current, corresponding to the south-east trade wind.

The *Northern* Equatorial Current was first described by Findlay (1853). It is a variable current, since it covers different areas of the ocean at different times of the year. Between 20° and 25° W. L. its southern boundary varies from 6° N. L. in March and May to 12° N. L. in September. The current charts for the Atlantic Ocean show a variation of from 5 to 30 sea-miles per day. Under the land on the African coast the drift is weaker, off the West Indian Islands stronger, than the average. The greatest velocity is in the period from December to June, when over 40 sea-miles is recorded.

The *Southern* Equatorial Current is met with from the eastward of 30° W. L. and to the south to 15° S. L. as a strong permanent stream. Our current charts show it in February and March as far west as the island of San Thome. In the meridian of Greenwich the northern edge of this stream is about 1° or $1\frac{1}{2}$° N. L.; in 10° W. L. it is 3° to 4° N. L., and continues in this position to 30° W. L.

The Equatorial Current divides at Cape San Roque, one part (*the Brazil Current*) running south along the coast of South America, the other running north-west. This north-westerly branch unites near the Amazon estuary with a branch of the Northern Equatorial Current, and then again with the main Northern Equatorial Current, all three ultimately continuing as the *Guayana Current*. This north-western diversion of the South Equatorial Current attains a velocity of from 30 to 60 sea-miles a day in the vicinity of Cape San Roque. The greatest velocity is 100 miles a day, which is attained in the northern summer.

The velocity of the equatorial currents is both large and

constant. Drift-bottle experiments show that in the Northern Equatorial Current over 45 per cent. of the bottles drift over 10 miles a day; and in the Southern Equatorial Current 54 per cent. show a daily velocity of over 10 miles and 23 per cent. of over 20 sea-miles, with a maximum of 28·8 sea-miles. These drift-bottles show that off the island of Trinidad there is a



FIG. 29.—CURRENTS OF THE ATLANTIC OCEAN.

certain mixture of branches of the Northern and Southern Equatorial Currents. Two bottles were found on the island in March, 1887, which had been released at widely different points in the previous year in the Northern (12° N. Lat., 26° W. Long.) and Southern (3·3° S. Lat., 16° W. Long.) Equatorial Currents respectively.

The Southern Equatorial Current exhibits one remarkable peculiarity. The surface waters in the equatorial region between 10° and 25° W. L. are appreciably (3° to 4° C.) colder in August than in February and May, and colder than the air above. To the south the water temperature is higher, so that a cold zone exists here on the Equator. This cold-water island is plainly marked on the English surface-temperature charts for August.

The prolongation of the chief branch of the Northern Equatorial Current together with the Guayana Current is known as the *Caribbean Current*. Rennell described this drift as, "not a stream, but a sea in motion." Our current charts give a drift of 24 to 72 sea-miles per day near the continental coast. This is the current that Columbus encountered off the coast of Honduras on his fourth voyage (1502), and found so disagreeable. This Caribbean Current enters the Gulf of Mexico through the Yucatan Channel between Yucatan and Cuba. The Yucatan Channel is only 100 miles across from Cape San Antonio to Cape Catoche—that is, only one-seventh of the diameter of the current in the Caribbean Sea itself. As a result of this construction the velocity of the current is considerably increased.

The warm Caribbean Current, after entering the Gulf of Mexico, runs due east and between Florida and Cuba, and then between Florida and the Bahama Islands out into the Atlantic Ocean. The current is now known as the Florida Stream or Gulf Stream. The latter name was given under a misapprehension, since the current does not enter the Gulf of Mexico proper. In the older English charts a branch of the Caribbean Current is shown running clockwise round the Gulf of Mexico through the Gulf of Campeachy past Vera Cruz and Tampico. As a matter of fact, west of the Mississippi delta the current runs in exactly the opposite direction, and is, in fact, the deltaic water deflected to the west by the rotation of the earth. The surface temperatures of the Gulf water prove conclusively that there is no marked influx of the Caribbean

Current into the Gulf. The May temperatures of the Gulf are :

The Isotherms of—	20° C.	15° C.	12·5° C.
	Metres.	Metres.	Metres.
In Yucatan Strait	212	370	465
Between Campêche Bank and Mississippi	110	220	305
Between Vera Cruz and Galveston ...	88	160	233

The average temperature of a column of water 700 metres deep is, in the Yucatan Straits, 16·36° C.; from the Campêche Bank to the Mississippi, 13·01° C.; from Vera Cruz to Galveston, 12° C.; while north of Havana it is 16·54° C.

Outside the West Indian Islands there flows a main branch of the North Equatorial Current—namely, the *Antilles Current.* This takes a westerly and north-westerly direction. Our current charts show, between the Eastern Antilles and the Bermudas, numerous westerly currents of a velocity from 8 to 20 sea-miles per day.

The Southern Equatorial Current is prolonged along the South American coast as the *Brazil Current.* This is a comparatively feeble current, and averages 20 sea-miles per day, and rarely exceeds 24 miles. The bulk of this warm water flows southward beyond the Tropic of Capricorn.

The *Guinea Current* flows along the African coast, between Cape Roxo and the Bight of Biafra, extending southward to the latitude of 3° N. Owing to the paucity of observations, its westerly boundary has not been exactly determined. It can always be traced as far as 23° W., but the statement* that it is met with as far as 53° W. is absurd, and its extreme westerly limits are probably not beyond 40° W. L.

It has been determined in November to 33° W. L.; in January to 27° W. L.; in March to 25° W. L.; and in May to 28° W. L.

The velocity of this stream is on an average 18 sea-miles

* Jackson, "The Principal Winds and Currents of the Globe," London, 1914.

per day, with maxima of 40 to 50 miles in certain areas. The Guinea Current is warmer than the Equatorial Current; only in the summer (August) has the westerly portion of the latter a higher temperature (over 28° C.). At this time the Guinea Current is cooler than in other months, probably because the rainfall of the south-west monsoon cools the surface waters. The density of the Guinea Current is less than that of the Equatorial, probably for the same reason, since it lies for the most part in the doldrums, with their calms and heavy rains. The sea off the coast of Upper Guinea is frequently cool, and for days at a time in July, August, and September is only 19° C. to 20° C. Farther from the coast and in deeper water the temperature at the same time is from 25·5 to 26·5° C., the normal temperature of the Guinea Current.

Along the coast between 4° and 7° W. L.—that is, off Cape Three Points—the water temperature is between 20° and 22° C., and similarly for the whole of the Slave Coast farther east. The breezes from the warmer Guinea Current flowing over this cooler water produce numerous fogs, which make this coast dangerous for navigation. Between the Bissagos and Cape Palmas this cold coastal water is not met with.

THEORY OF THE ATLANTIC EQUATORIAL CURRENTS.—These currents lie in the region of the trade winds and the doldrums (or "horse latitudes"). The north-east trade wind is strongest in winter; in February between Cape Verde and the Guayanas it blows with a strength of 5 to 6 on the Beaufort scale, its direction being in its easterly area north-north-east, in the centre at 40° W. L. about north-east, and off the Lesser Antilles east-north-east.

The south-east trade is not so strong, being at the most 4 on the Beaufort scale. Its direction is between 5° and 10° S. L., west of south-west; eastwards from Ascension more south-south-east; and eastwards of the Greenwich meridian south; on the African coast south-south-west to south-west.

Near to the Equator, and especially near the calm zone, the south-east trade comes more from the south, and in its northern

area more south-south-west and south-west. At its northern limits its strength falls much below 4 of the Beaufort scale, and calms are frequent.

In the northern summer the whole system shifts in a northerly direction, and the zone of calms is broader, especially in the sea off Cape Verde. The strength of the north-east trades is usually the same as in winter in two areas only—namely, north from Cape Verde in a north-easterly direction and by the Lesser Antilles. Within the zone of calms a so-called south-west monsoon develops. The south-east trade blows in summer with greater force, over 5 on the Beaufort scale, in the westerly region between Fernando Noronha and Ascension.

These trade winds must produce surface currents. In the northern summer, when the south-east trade blows strongest, the velocity of the Southern Equatorial Current reaches its maximum. The Northern Equatorial current also waxes and wanes with the north-east trade winds. Moreover, in the open ocean currents purely due to the wind have been determined in numerous localities. For example, in the area between 10° and 16° N. L. and 35° and 40° W. L., in the month of February, the average direction of the wind is south 51° east (from 256 observations). The corresponding currents in this area give a direction of north 81° west, a difference which is due to the deviation of the current to the right from the wind's direction. The deviation (279° to 231°) amounts to 48°, and is due to the earth's rotation. The Southern Equatorial Current is driven by the south-east trade wind to Cape San Roque, when it divides into two branches, one running north-west, the other south. Part of the north-west arm (the Guayana Current) and the south arm (the Brazil Current) are bent back on themselves into the South Equatorial Current.

The Guinea Current is not to be attributed solely to the wind, especially in summer, when the south-west monsoon blows.

In a typical region (from 15° to 25° W. Long. and 5° to 10° N. Lat.) the average direction of the wind is south 29°

west; the current, however, is north 79° east. The deviation of current from wind (79° to 29°) is here 50°, which is rather more than would be expected from theoretical considerations. The south-west monsoon has, in these regions, an average strength of 3·66 on the Beaufort scale—that is, a drift of about 12·3 sea-miles per day, whereas the Guinea Current averages 20·6 sea-miles. So that the wind drift only accounts for about three-fifths of the velocity of the current. In winter the south-west monsoon falls entirely, so that at this time the Guinea Current cannot be due to the wind. The Guinea Current is partly a *compensation current*, a counter equatorial current flowing eastwards between the North and South Equatorial Currents.

A third cause of the Guinea Current is the difference in density between its waters and those of the neighbourhood. The Guinea Current has a smaller salinity than either of the equatorial currents. The lines joining places of equal density (isohypsal lines) run as a rule from west to east. As a rule the current runs parallel to the isohypsal lines. The compensation current and the differences in density account for two-fifths of the velocity of the Guinea Current, but of these the former has undoubtedly the more important influence.

Broadly speaking, the Guinea Current is a compensation current between the two equatorial currents, although there are not unimportant differences of density, and in summer the south-west monsoon plays a part in its causation.

2. The Florida Current (so-called Gulf Stream).—The Florida Current, under its popular but misleading name of Gulf Stream, is the best known, best defined, and most remarkable of all oceanic currents. Incidentally it is the current which most influences the climate of the British Isles and the shores of North-Western Europe. First noticed by Juan Ponce de Leon in 1513 on his voyage through the Florida Straits from Porto Rico, the Florida Current has been extensively investigated, more particularly by American hydrographers, since the middle of the nineteenth century.

In the narrowest parts of the Florida Straits, especially between Bemini Keys and the mainland, the current attains a velocity not recorded in the case of any other ocean current. The yearly average is 72 miles per day, but in the coldest and warmest seasons from 100 to 120 miles is attained. This is from 1·5 to 2·5 metres per second—*i.e.*, more than that of the Mississippi between Ohio and Arkansas, 1·91 metres per second. With prevailing northerly winds the force of the current is much increased, but with a barometric depression over the Gulf of Mexico the reverse is the case, and water rushes into the Gulf. The northerly winds are met with when there is a barometric maximum over the Gulf or over Texas or Louisiana. Consequently, in the Florida Channel the strongest current runs against the wind—*i.e.*, the north-east wind and *vice versa*.

Under average conditions the axis of the greatest velocity of the current is to be found:

	Miles.
In Yucatan Strait east of Contoy Island	35
North of Havana	25
East of Fowey rocks (Florida)	11
East of Jupiter Inlet and Fort (Florida)	19
South-east of Cape Hatteras	38

The current shows many variations in direction and strength. Along the Florida reefs a counter current setting south-west and west into the Gulf is occasionally met with. According to Pillsbury, the velocity in knots measured 6·5 metres under the surface is as follows:

Between Tortugas and Havana.		East of Fowey Lighthouse.	
Distance in Sea-Miles.	Average Velocity in Knots.	Distance in Sea-Miles.	Average Velocity in Knots.
20	0·32	8	2·66
35	0·74	11½	3·46
50	2·24	15	3·16
68	2·23	22	2·73
86	0·77	29	2·12
		36	1·71

In the Florida Channel there are periodic variations in the direction and strength of the current, and according to Pillsbury these are connected with the declination of the moon; with greater declination the current is bent to the left, and with less declination to the right, of the normal. With higher declination the current broadens; with lower declination it contracts. With the broadening of the current there is a decrease of temperature; with the contraction an increase, the former being due to the rise of deep water to the surface. The axis of the stream is, at high declination, 16 and at low declination 34 sea-miles from Cuba, north of Havana; in the narrows it lies at high declination 7, at low declination 15, sea-miles east of Fowey Lighthouse.

In the narrows the Florida Stream is 30 miles wide; after its exit from the Channel in the neighbourhood of Cape Canaveral it is 60 miles and at Charleston from 120 to 150 miles across. This steady broadening of the current as it proceeds to the north takes place for the most part in an easterly direction; to the west the edge of the current keeps close to the 200-metre line. Here the boundary is so distinct that it is plainly visible from the deck of a ship. As the stream widens its velocity decreases. In the latitude of New York, where the current runs easterly, the velocity is 72 miles on occasion, but the average is more like 48 miles per day. Farther east it is less than 30. Off the coast of North America the Florida Stream can only be determined to 45° W. L.—that is, off the eastern edge of the Newfoundland Banks. Even in the latitude of Cape Hatteras alternate warm and cool currents are met with. These cold bands are not counter-currents of Arctic water running south-west or west, but branches of the Antilles Current which, running outside the Bahama Islands, unite or mingle with the Florida Current. The latter is relatively warmer than the Antilles Current. Both run together for a while, the Florida Current above the other. The strength of the Florida Current wanes appreciably to the eastward of 60° W. Lat.

The Origin of the Florida Current.—According to Franklin, the trade winds force the oceanic water into the Caribbean Sea, and as a result the water is forced out through the Florida Channel into the Atlantic. This theory holds the Florida Current to be purely a drift current. The whole of the Caribbean Sea has a strong westerly drift, and this water must pass out through the Florida Channel, since the Gulf of Mexico is a closed area.

Another theory is that the Florida Current is due primarily to the differences in density between the Gulf of Mexico and the neighbouring ocean. As a whole, the waters of the Gulf are colder than those of the ocean, and on this ground the level in the Gulf should be lower. The salinity in the Gulf is approximately 35 per mille, which is less than that of the Florida Current. The level of the Gulf on a Galveston-Vera Cruz section can be calculated to be 65 centimetres lower than that of the Yucatan Channel. By similar reckoning the level between the Yucatan Channel and the Florida Channel north of Havana on the Bemini Keys section is approximately identical.

In winter strong westerly and north-westerly winds prevail over the whole oceanic area between the New England coast and the Azores. These winds are a cause of a depression in the ocean level north of 30° N. Lat., and this is also a contributory cause in the origin of the Florida Current. In summer between Halifax and the Bermudas the prevailing winds are from south and south-west, and these, again, help the Florida Current.

On its left hand the current is bounded by the "cold wall," which is sharply marked off, its surface temperatures being from 10° to 15° or even 20° C. below those of the Florida Current. On its right hand the current's boundary is by no means sharply marked off.

Farther west in the Atlantic the Florida Current has several main branches. The Antilles Current furnishes it with an important constituent, and its common branches take several

main directions. The principal (the so-called Gulf Stream) moves north-east. Another branch takes a south-easterly direction past the Azores, and reaches the African coast as the Canaries Current. Between the extreme north-easterly and south-easterly branches we find the Florida Current, supplying the coasts of the British Isles, the North Sea, the Bay of Biscay, and the Mediterranean through the Straits of Gibraltar, with warm tropical water. The velocity of the current is now relatively feeble. Along a line between the United States coast and the English Channel the current is rarely 48 miles per day, and the farther east one comes the weaker is the current; on the average it is not more than 12 to 15 miles a day. The direction is not constant, and depends largely on the wind.

The warm water of the Florida Current which flows between the Newfoundland Banks and the Bermudas runs then in an easterly direction to the Azores, where it passes over into the Canaries Current, and this, again, into the North Equatorial Stream by Cape Verde. Consequently, there is in this region of the North Atlantic an anticyclonal drift around a centre which is located between the Canaries and the Bermudas. In the central area is the so-called Sargasso Sea, in which on all sides the currents bend to the right.

Numerous wrecks and flotsam drift across in the winter storms from the American coast to the neighbourhood of the Azores.

The marine plants (Fucoids) known as *Sargassum bacciferum* and allied species are shore forms which flourish in the warm water of the American coasts up to Cape Cod, but more especially on the rocky West Indian islands. They are broken off by the waves of tropical storms and float in the Florida Current, and are thus distributed over the whole of the North Atlantic. These plants were found by Columbus. Humboldt investigated the distribution of this "Gulf-weed," and described two banks, one between Flores and Corvo from 40° W. Long. to 20° N. Lat., and a second smaller bank at

70° W. Long. Between these two banks are a chain of connecting banks. Humboldt thought they grew on the bottom *in situ*, but there can be no doubt they are all derived from shallow water of the American coasts. Humboldt's banks are really the trade routes for sailing vessels, and since his information was mainly, if not solely, derived from shipmasters, his notifications of the presence of the Gulf-weed are naturally most abundant from the routes frequented by sailing ships making their passage across the Atlantic. The prospect of a ship reporting the Gulf-weed in an area of 11,000 square kilometres is only 1 in 8, and for the greater part of the surface 1 in 12 or 1 in 20 only. The maximum prevalence of the Sargassum is in the oval area between 21° and 35° N. Lat. and 40° and 73° W. Long.—that is, in the "Sargasso Sea."

Rarely the Sargasso "weed" is found in Irish, English, and French coastal waters, and even occasionally in the North Sea and Western Mediterranean.

The Canaries Current.—The Canaries or North African Current runs south along the West Coast of Africa at the eastern boundary of the north-east trades, between Madeira and Cape Verde Islands. Its velocity is moderate, from 8 to 30 miles per day, but records above 15 miles are exceptional. The current carries water from high latitudes into the equatorial regions, and consequently is a cold current. The main body of the Canaries Current runs into the North Equatorial Current, and only a small part is continued along the African coast in a south-easterly and easterly direction as the Guinea Current. There are considerable differences in temperature between the Canaries and Guinea Streams. The southern boundary of the Canaries Current is much farther south in March than in September. The origin of this current is to be sought in the prevailing winds, together with the configuration of the West Coast of Africa. The prevailing winds are north-west and north.

The Canaries Current is not a pure drift current, but is caused by the diversion of the North Equatorial Current from

the African coast, on to which it has been blown by the north-east trade winds.

Cold water is found along the North African coast from Cape Verde to the Straits of Gibraltar, and in summer even farther north. There are periodical variations, the cold-water boundary being farther north in summer and farther south in winter. Off the mouth of the Gambia River in February and March, sea temperatures as low as 18·3° C. have been recorded, in contrast to the river-water temperature of 24° C. In the Bay of Arguin in August 17° has been recorded for surface temperatures, which is 5° less than that of the Canary Isles and Madeira. Off Mogador in November 16·1 has been observed, contrasted with 20·5 in the open sea 200 miles from land.

The cold water has a dark grey to bottle-green colour, and, since the atmosphere above is much warmer, is a frequent source of fog. This cool influence is felt along the Portuguese coast as far as 40° N. Lat.

The north-eastern branch of the Florida Current has no special name, though it is precisely that current which is popularly referred to in the British Isles as the "Gulf Stream." A modern name for it is *Atlantic Current.* Since it washes the western shores of the British Isles, Krümmel has called it the *Irish Current.* This current becomes separated off from the Canaries Current, and forms the northerly branch of the combined Florida and Antilles Currents. The prevailing south-westerly Atlantic winds drive the warm-water current to the north-east, into the English Channel, and through the Straits of Dover into the North Sea. Another branch runs around the west of the British Isles and reaches Norway. The main part of the North Atlantic drift or *Irish Current* is in the open ocean, where it is met with off the Faroes and on to Iceland. From Iceland it flows on to the west and south-west as the *Irminger Current,* which, with the cold East Greenland or Arctic Current, runs to Cape Farewell. Ultimately it joins with the Labrador Current, runs south and south-west, completing its cycle off the American coast. There

is a cyclonic circulation in the upper surface waters of the North Atlantic. This is established not only by water temperatures and salinity, but by drift-bottles as well.

Floating bottles from Franz Joseph's Fiord in East Greenland have been picked up in North-Western Ireland and the Hebrides. The velocity of the current in this circulation is extremely slight, and on the average attains 10 miles per day.

Counter-currents occur, and this makes the identification of the circulation difficult. A more detailed consideration of this area is given elsewhere (p. 190).

The general easterly drift in the North Atlantic produces an east-going current at the entrance to the Bay of Biscay. A Biscayan current was first described by Rennell in 1793, and was known as *Rennell Current*. It was stated by Rennell to run along the north coast of Spain across the French coast to the north and north-west, and thence straight across the entrance to the English and Bristol Channels. M. Hautreux proved from a large number of drift-bottle experiments that this current does not exist! Probably in the Bay of Biscay the currents follow the wind.

There appears to be a current running east or east-south-east into the Bay, since a large number of drift-bottles are washed up between the Loire and the Gironde, most of which come from the north-west—that is, exactly opposite to the so-called Rennell Current. On the other hand, not a single bottle thrown out between Ushant and Finisterre was recovered from a north-westerly direction.

Reports collated from sailing vessels show, in the western half of the Bay of Biscay, a current in January running south 40° east, with a velocity of 12·7 sea-miles per day; and in July south 30° east, with a velocity of 14·1 sea-miles per day. The stability or frequency is, however, small—in January 14 per cent. and in July 42 per cent. In the coastal regions of the north of Spain there is an easterly current, especially in winter; in summer, with a barometric depression over Spain and a north-east wind, the current runs west.

Some practical seafarers still speak and write of *Rennell Current*. Occasionally sailing ships coming from the westward find themselves in the Bristol instead of the English Channel. This is due to bad weather preventing any astronomical observations for some days. This has been attributed by some navigators, not to a current, but to the deviation of the compass, or even to tidal streams.

Be that as it may, there is no reason for perpetuating "Rennell Current!"

In contrast to the North African branch of the North Atlantic (easterly) Current, the Irish Current is split off from the main stream by the earth's rotation, and impinges on the continental shelf.

The continuation of the Irish Current in a northerly direction towards Iceland has been investigated thoroughly during the last few years, particularly by the Danes. Irminger, as a result of 87 observations between Fair Island and Iceland, found the average direction of the current to be north 52° east, with an average velocity of only 2·4 sea-miles. There are, however, many eddies in this current. Near the Shetlands the stream runs more easterly, but near Iceland north-easterly. On the Faroes much floating wood from the West Indies was stranded at this time in the months of February and March. Irminger discovered that the current coming from a southerly direction impinged on the Iceland coast in the neighbourhood of the Vestmann Islands, and thence flowed west.

There is an important trawl fishery carried on in Icelandic waters, mainly by British steam trawlers. North Sea water mixed with that of the Atlantic, and thereby warmer and salter, is forced over the Faroe ridge. Isothermal lines are bent sharply against the coast.

The Irminger Current.—Irminger was also the first to investigate the conditions west of Iceland to Davis Strait. The prevailing direction is here west of north, the velocity slight.

The *Irminger Current* fills the whole area between Iceland and Cape Farewell, with the exception of a varying coastal zone occupied by the ice-bearing East Greenland Current. With an off-shore wind the latter broadens out to sea, covering the Irminger Current with a thin film; its cooling effect is felt, however, to depths of from 125 to 250 metres.

The currents in Davis Strait, to which a branch of the Irminger Current belongs, are clear when one considers the cold currents—namely, the East Greenland Current and the Labrador Current.

A high-pressure area over the northern part of North

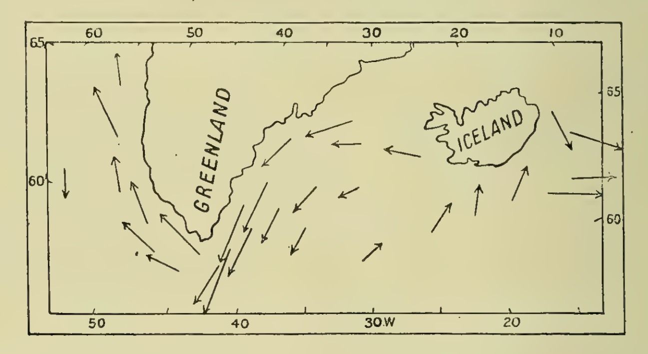


FIG. 30.—SURFACE CURRENTS IN THE NORTH-WEST ATLANTIC (IRMINGER CURRENT). (KRÜMMEL.)

The length of the arrow is proportional to the length of the current (1 centimetre per second = 0·7 millimetre).

America produces a gradient on the coasts of Baffin's Land and Labrador, with a prevailing wind east-south-east; the current is driven south by east—that is, along the coast in the eastern part of the Strait.

In the western half of Davis Strait the water flows in from the south. This is Atlantic water from the Irminger Current. Along the east coast of Greenland, owing to barometric minima over the land, the prevailing winds are northerly, and consequently the drift of the water is to the south-west. The water here is colder and with a lower salinity than that of the Irminger Current, since it contains much floating ice and

water resulting from its melting. There is, consequently, on the east coast of Greenland a higher sea-level, due to the presence of this light (in density) water. This increase of level is on the east coast of Greenland 15 centimetres and on the west coast 40 centimetres as compared with the mean level of Davis Strait. Consequently a current flows not only along the land down the east coast of Greenland, but also around Cape Farewell and up along the west coast. This current is also assisted by the secondary barometric minima on the east side of Davis Strait, which produce a south-east wind and consequently a drift of water to the northward. The East Greenland or Arctic Current brings ice with it, so that the southernmost harbours of the west coast of Greenland—Julianshaab and Frederikshaab—are bedecked with ice for weeks at a time when, owing to the melting of the ice in the warmer Atlantic water, the harbours on the west coast in higher latitudes from 64° to 65° N. Lat. are free from ice, and the sea east of 55° W. Long. is similarly free.

The suction of the Labrador Current certainly draws part of the East Greenland Current straight across the Straits to the west. The deeper waters of Davis Strait are warmer and of a high salinity (34·4 per mille), and consequently of Atlantic origin. The old idea of a sinking of the East Greenland Current under the warmer West Greenland Current must be abandoned, because its water is of less density. The older idea of the East Greenland Current making straight across to the Labrador coast is also not in accordance with modern investigation. The origin of the West Greenland Current from the warmer Irminger Current is also established by drift-wood. Mahogany-trees have been found washed ashore on the south point of Greenland and on Disco Island as well. This drift-wood is becoming scarcer of modern times, owing to the settlement of the American coasts.

The velocity of the East Greenland Current is from 5 to 10 sea-miles per day, being less nearer the land. The ice-field drifted for 243 days on an average 4·6 miles per day.

The velocity of the Labrador Current in Baffin Bay and Davis Strait can be estimated from the drift of nineteen men of Hall's Polar expedition (the *Polaris* of New London, U.S.A.), who on pack-ice drifted from October 15, 1872, to April 30, 1873), between 74° and 69° N. Lat. in the middle of Baffin Bay, an average of 6¼ sea-miles daily to the south. The crew of the steamer *Tigress* drifted in 53° N. Lat. off the coast of Labrador, 11·8 sea-miles daily.

The relationship of the Labrador Current to the so-called "Gulf Stream" and to the line of separation known as the "cold wall" is by no means fully understood, although there have recently been considerable additions to our knowledge of the area on and surrounding the Newfoundland Banks.

The Labrador Current coming from the north-west strikes the coast of Newfoundland, flows over the easterly part of the Grand Bank, and ends up in the Gulf Stream east of 50° W. Long., so that its waters do *not* wash the east coast of the United States.

On the Newfoundland Bank there is no constant stream in any direction, so that no Arctic water flows to the south-west over the bank past St. John's and Cape Race. The coastal currents of the United States originate exclusively from the Gulf of St. Lawrence—that is, the "Cabot Current"—and these run down to the latitude of New York. South of this and south of Cape Hatteras there is a current which has a temperature only slightly below that of the Florida Current, possibly only 2° to 3° C. less, and consequently is entirely different from the "cold wall" water met with farther north, which shows a drop in temperature of from 15° to 20° C. When one current ends in another there must be a mixture of the component waters. The Labrador Current is not simply swallowed by the Florida Current.

The older charts show the Labrador Current as disappearing under the Gulf Stream drift. Deep-sea observations from this region are remarkably scanty, but the *Challenger* records between 35° and 36° N. Lat. and 55° and 45° W. Long. show

no remarkable cooling of the deeper layers, and, so far as they go, the records show no trace of the submergence of the Labrador Current.

There can be no doubt that the Labrador Current flows over the eastern edge of the Grand Bank. The water temperature and the presence of drift-ice and icebergs confirm this. The current runs south-south-west. A mass of icebergs also drifts to the southern extremity of the bank, and some of these drift westerly into the steamer route. One such caused the

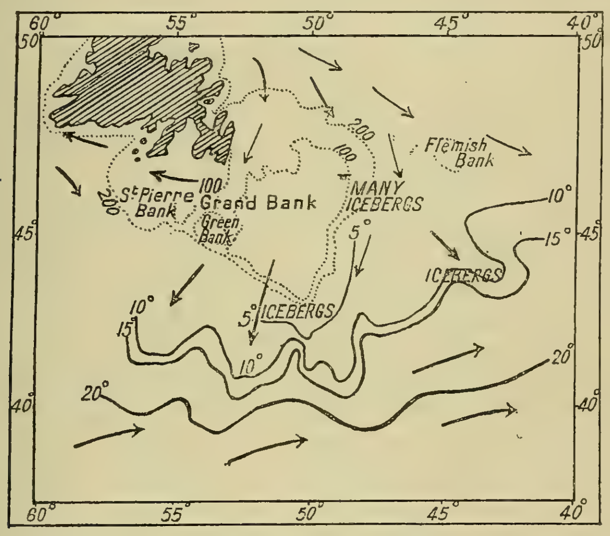


FIG. 31.—SURFACE TEMPERATURES ON THE NEWFOUNDLAND BANKS. (DINKLAGE.)

loss of the *Titanic* on April 15, 1912, in 41° 16′ N. Lat. and 50° 14′ W. Long. (see Fig. 31).

Icebergs have been observed from and in the vicinity of Sable Island (south of Nova Scotia). In winter and early spring drift-ice, but no icebergs, comes out of the Gulf of St. Lawrence with the Cabot Current, and goes south and west.

The drift-ice charts, especially in years when ice is abundant, show by the distribution of icebergs that the Grand Bank is by no means free from currents. The southern and eastern limits of ice in the North-Western Atlantic vary from

month to month and year to year. In the early months of the year the whole of the northern portion of the Grand Bank is covered with icebergs of varying size, some so large that they are undoubtedly aground. There is a relatively deep channel on the south-east side of Newfoundland, which separates the Grand Bank from St. Pierre Bank and Green Bank. The depths between the banks are over 100 and for the most part over 150 metres. Through this channel it is easy for a branch of the Labrador Current, with its icebergs, to pass. The Labrador Current also flows east and north-east over the Flemish ridge (east of the Grand Bank), and in some years this cold and light water extends to 40° W. Long. In this way icebergs drift into the Irish Current extension of the so-called Gulf Stream drift. Some of the icebergs make enormous journeys before they finally disappear; for instance, they have been observed in 51° N., 11° W.; 51° N., 19° W.; 48° N., 15° W.; 53° N., 22° W.; and on one occasion just west of Mull Island in 56·5° N., 6·5° W.

The transitional zone between the Labrador Current and the Gulf Stream is shown by the isothermal lines (Fig. 31). Tongues of cold water project into the latter, notably due south of the Grand Bank, one between the Grand Bank and the Flemish ridge, and two south-east of the Grand Bank.

3. The South Atlantic Currents.—(1) *The Brazil Current.*—The main drift of the Brazil Current as a branch of the South Equatorial Current has already been mentioned. It flows along the Brazil coast.

According to the older German charts, the Brazil Current splits up at 30° S. Lat. into two main branches. One flows over the coastal banks of Patagonia, and then farther south to Cape Horn. The second branch is deflected to the east, and north of 40° S. Lat. is known as the Southern Connecting Current, running across the ocean east and then north-east. The English current charts show the Brazil Current as disappearing in 30° to 35° S. Lat., and over the Patagonian banks a current flowing from the Pacific Ocean round Cape

Horn to about 43° S. Lat. This current will be noticed as flowing in an entirely opposite direction to that shown on the older German charts. The English charts also show a connecting current in 30° to 35° S. Lat. flowing across to the Cape of Good Hope. This connecting current was first described by Rennell, and it follows the course of the south-east trades to the Indian Ocean.

From numerous temperature observations it is clear that the Brazil Current flows to the south, and is separated from the coastal banks by water that is always from 6° to 10° C. colder (see Fig. 32). Over the banks themselves the water is nevertheless slightly warmer than that of the cold Falkland Current. Sailing ships on the outward journey round Cape Horn, battling against the prevailing south-west winds, constantly record ups and downs in the water temperatures from day to day as they cross and recross the boundary between the Brazil and the Falkland Currents.

Cape Horn ships on their homeward journey almost always record meeting warm water, from 3° to 5° higher than that previously met with, north-east of the Falkland Islands in about 50° S. Lat. This is the southernmost extremity of the Brazil Current. The accompanying figure shows that this current before it attains 49° or 50° S. Lat. turns to the eastward, so that around the Falkland Islands cold water is invariably encountered.

It is very improbable that the Brazil Current splits off the La Plata estuary, and that a narrow branch runs down along the coast. The temperature records are against this theory, as well as the actual current observations. Of 458 records of good reliability taken on the coastal banks, 321 show a northerly current between east-north-east and west-north-west—that is, 70 per cent. of the total. Some of these current records show considerable velocity—16, 20, and even up to 33 sea-miles per day. As soon as the boundary between the warm and cold waters is passed by ships on a south-westerly course, this northerly drift is observed. Wilkes noted this in

1839; as soon as the temperature sank from 19·4 to 13·9 the current ran in a northerly direction.

Temperatures over the Patagonian Bank are slightly warmer near the coast, but this coastal water is still from 3° to 4° colder, even in the southern summer, than the waters of the Brazil Current. The increase here is doubtless due to the sun's rays, which are powerful in this dry, hot climate, and this is

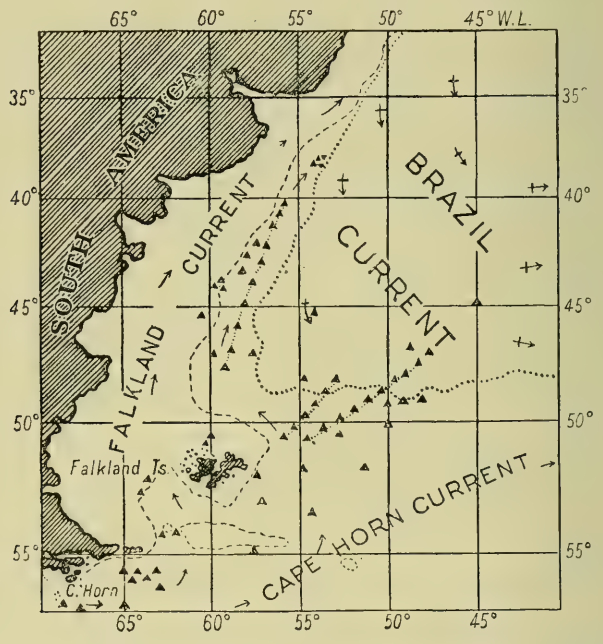


FIG. 32.—CURRENTS OF THE SOUTH-WEST ATLANTIC. (KRÜMMEL.)

borne out by the fact that the higher temperatures are purely superficial.

Drift bodies also support the evidence in favour of the Falkland Current. Large masses of *Laminaria* and *Macrocystis* are met with off the La Plata estuary drifting north-north-east. Darwin found this seaweed only rarely on the Patagonian coast as far as 43° S. Lat., and it only flourishes in abundance in the Straits of Magellan and on the Falkland Islands. Undoubtedly that met with off La Plata has drifted

far north. Another indication of the northerly drift of these currents is found in the distribution of icebergs. This is shown on the chart.

There is also a cold current branching off from the Cape Horn Current south of the Falkland Islands, and running northwards to the east of the islands. This joins the main Falkland Current, which runs up the whole coast of Uruguay and South Brazil to Rio Janeiro and Cape Frio. In this current the cold waters extend to considerable depths. A deep-sea sounding of the *Challenger* expedition in 42° 32′ S. Lat. and 56° 29′ W. Long. gives a temperature of 2° at 274 metres; in the neighbouring Brazil current in 41° 51′ S. Lat. and 54° 48′ W. Long. the 2° isotherm is found at 2,960 metres.

The Falkland Current is bottle-green; the Brazil Current, on the other hand, has the deep blue, high salinity water of the tropics. The cold green water is rich in fish life.

(2) *The South Atlantic Connecting Current* is a continuation of the easterly deflected Brazil Current, as well as the north-easterly Cape Horn Current. Rennell describes this current as connecting in the high southern latitudes of the Indian and Pacific Oceans currents which run in the direction of the earth's rotation from west to east.

The average annual barometric pressure gives gradients to the south in 35° S. Lat. In 40° S. Lat. the prevailing wind drives the water east or east-south-east; in 55° south to the east by south. A drift to the east-north-east results.

The strength of the connecting current varies considerably with the wind. According to the British charts, the velocity is between 6 and 33 miles per day. The *Challenger* found between Tristan da Cunha and the Cape of Good Hope a direction north 27° east, and a velocity of 15·8 sea-miles per day.

(3) *The Benguela Current* is the South Atlantic counterpart of the Canaries Current. From the South Atlantic Connecting Current a branch is split off to the left to the South African coast, going to the north behind the south-east trade drift.

From Table Bay northwards to the Congo estuary this cold current runs with an average velocity of 12 miles per day, the rare maxima being 30.

Near the land the current is feeble and irregular, although it is strong enough off the mouth of the Congo to drive the river water north-west into the open ocean. Drift-wood from the Congo is often found in the neighbourhood of St. Thomas Island.

As a result of the prevailing winds the cold Benguela Current flows up along the West African coast to the Congo estuary.

There is thus also in the South Atlantic a circular system of ocean currents running counter-clockwise. In the centre of this system, between 20° and 35° S. Lat., is a zone of feeble winds and currents with high barometric pressure, in this respect resembling the Sargasso Sea.

Deep-Water Currents of the Atlantic.—Very little is known of the currents in the deeper layers of the great oceans. Vertical circulation of the ocean waters depends on three main causes :

(1) The pull of the winds on the surface waters resulting in upwelling.

(2) Differences in salinity between different layers of water.

(3) Differences in temperature causing differences in density.

Schott in the Valdivia report gives a temperature profile for the Atlantic Ocean (see Fig. 33) to a depth of 2,500 metres (1,367 fathoms). It is seen that there is a marked influx at depths of from 1,500 to 2,500 metres (820 to 1,370 fathoms) of cold water of 3° C. and less from high southerly latitudes, and this reaches as far as the Equator, and may even be traced to 20° N. Lat.

Apparently there is a current from the north, which is ascertainable in from 55° to 25° N. Lat. moving south. It is well known that there is a mixture of Arctic and Atlantic water at depths of 500 to 550 metres (273 to 300 fathoms) on the ridge

which runs from Scotland to the Faroes and thence to Iceland and Greenland. The isotherms of 5°, 10°, 15°, and 20° show a downward curve between 25° and 35° north and south latitudes, whereas in the equatorial regions they lie quite near the surface. To account for the temperature distribution warm and cold vertical currents are shown in the diagram, upwardly-directed cold currents in the equatorial region, and downwardly-directed warm currents in the temperate regions.

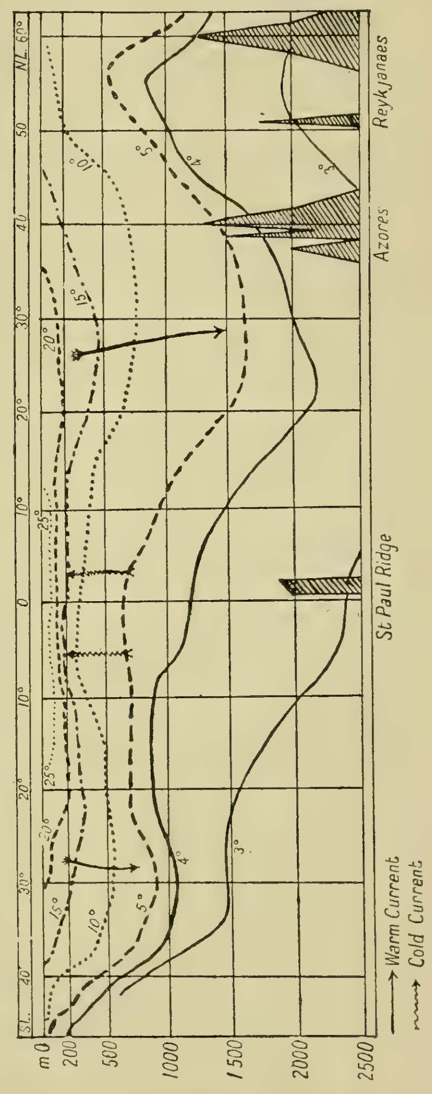


FIG. 33.—TEMPERATURE SECTION OF THE ATLANTIC ALONG 30° W. LONG. (G. SCHOTT.)

The regions in which the isothermal lines bend upwards towards the surface are precisely the central regions of the great circular currents—*e.g.*, between 25° and 35° N. Lat.

The influence of *density* on vertical circulation is naturally most important.

As an example of the drift of water due to differences in salinity let us take the outflow of Mediterranean water into the North Atlantic. At depths of 1,000 metres (547 fathoms)

Mediterranean water pours out into the Atlantic and flows along the Portuguese coast in a northerly direction.

There can be no doubt from the salinity determination that in this section of the North Atlantic (see Fig. 34) the Mediterranean water runs underneath the Irish branch of the Florida Current. The extreme westerly branches of this Mediterranean Current are found west of Ireland in 52° and 53° N. Lat., where the Mediterranean salinities are found at depths of 328 to 656 fathoms. At 57° N. Lat., off Rockall, all trace of

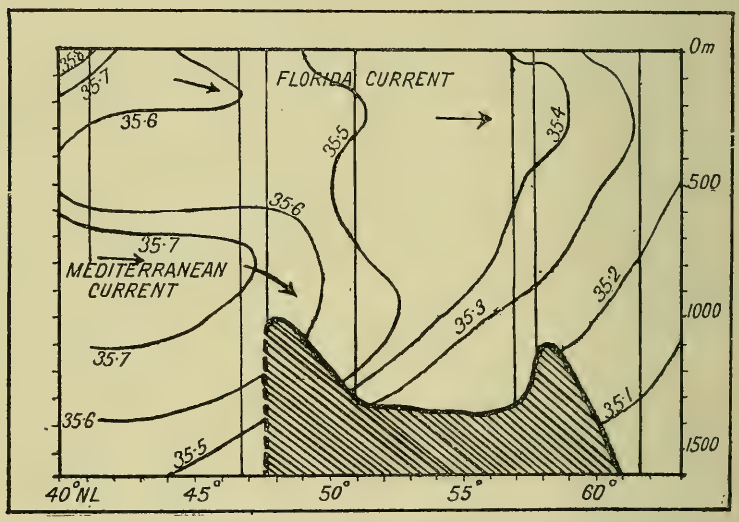


FIG. 34.—MEDITERRANEAN BOTTOM CURRENT DUE TO DIFFERENCES IN SALINITY, ON A SECTION FROM THE BAY OF BISCAY TO ICELAND. (KRÜMMEL.)

this deep high-salinity water is lost. The highest salinity in the surface layers is met with in depths of 100 to 164 fathoms, and is due to the Irish branch of the Florida Current, which in its surface layers becomes diluted with heavy rainfall the farther north-east it gets. The salinity of the deeper layers of the other parts of the North Atlantic—*e.g.*, the Labrador Current—are little known, certainly not enough to generalise about.

ENCLOSED AND PARTIALLY ENCLOSED SEAS OF THE NORTH ATLANTIC.—The currents of the *Mediterranean* were first

described by Smyth, who worked there from 1810 to 1824. The main stream runs in from the Atlantic through the Straits of Gibraltar, and then in an easterly direction along the north coast of Algeria, round the corner at Tunis, and so south, past Sicily and Malta, to the Gulf of Sidra. Thence it flows along the Tripoli coast until it attains the harbour of Port Said. After this its direction is northerly along the Levant, and so along the south coast of Asia Minor, its direction now being westerly. It now runs past Crete on both sides, then north-west into the Ionian Sea. In the Adriatic the current has a circular counter-clockwise direction, up (northerly) along the Dalmatian coast, down (southerly) along the Italian coast.

The main current runs north-west in the Tyrrhenian Sea, west through the Gulf of Genoa, finally completing the circle by a south-westerly run along the Spanish coast.

Although Smyth's description of the counter-clockwise current is, in the main, correct, there are sundry points of detail which do not quite fit in with the general scheme. The currents in the Mediterranean are to a large extent pure drift currents—*i.e.*, dependent on the wind—and so vary from place to place. Nearly a century after Smyth's observations, the Danish investigation steamer *Thor* traced this current, which contained Atlantic plankton, along the north coast of Africa, in the general direction indicated by Smyth, as far as the Nile Delta.

The counter-clockwise current in the Adriatic has already been mentioned. The northerly current is noticeable off the Ionian Islands; off Corfu a branch is given off towards Cape San Maria di Leuca, but the main stream runs up past Cape Glossa. Along the whole coast of Albania and Dalmatia the general tendency is to the north-west. The current is deflected by the Istrian peninsula, and then runs along the east coast of Italy to the Straits of Otranto, where it unites with the currents running westerly from Corfu and Fano.

In the *Ægean Sea* the prevailing wind in summer is a strong northerly one (the Meltemia), and this produces on the

west side of the sea a strong and steady current in a southerly direction. On the Asiatic side a northerly current prevails. From the Dardanelles there is a strong outward current of low salinity which takes a south-westerly direction. This Dardanelles water is turned to the north (right) by the earth's rotation, which, combined with the prevailing north wind, drives it in a south-westerly direction around the islands of Imbros and Lemnos and on to the Eubœan coast. This current is very strong off Andros and Tenos, where it attains an hourly velocity of from 1·5 to 2 miles. Afterwards it takes a more southerly trend past Cape Malia, then through the Straits of Cervi to the west.

The currents in the Bosporus, Sea of Marmora, and the Dardanelles, run out into the Ægean Sea. With strong south-westerly winds there is, however, a feeble current in the reverse direction. In the Dardanelles the mid-current runs at from 3 to 5 miles per hour. These currents are due to the differences in density between the Sea of Marmora and the Ægean. In addition to this surface current, there is a counter-current in the reverse direction below 10 to 30 metres.

The currents in the Bosporus were known to the ancients. They are very strong, and there is a daily periodicity, with a minimum at night and a maximum a few hours after midnight. There is also a yearly periodicity due to changes in level in the Black Sea, which is highest in spring. The surface current here has a salinity of 20 per mille, the deeper counter-current 36 to 38 per mille (Ægean water).

The currents in the *Black Sea* change with the wind. The general tendency on the west side is to the southward, and thence through the Bosporus, though only a portion of the current goes through, the remainder continuing on to the east and forming a counter-clockwise current through the whole area.

The bottom currents of the Black Sea have been investigated by Wrangel and Spindler.

The entry of salt water into the Black Sea through the

Bosporus is very small in volume, since the depths there are only 42 to 48 metres. With strong south-west winds the surface currents are driven back into the Black Sea, and a certain amount of water of high salinity enters that way. Similar conditions obtain in the Baltic, where investigations have been more sustained and more thorough.

In the Straits of Yenikale similar conditions obtain to those described for the Bosporus.

In the later Miocene period the whole of the Aral-Caspian area was a continuous sea, shut off from communication with the ocean or with the Mediterranean. At the end of the Miocene period this Sarmate Sea was divided up into the Black and Caspian Seas. The latter was at that time united with the Sea of Aral. Later, in the Quaternary period, the isthmus separating the Black Sea and the Mediterranean was ruptured and communication established between them. Water flowed from the latter to the former, which was at a lower level, and its greater depths are now filled with water of high salinity, destroying the previously existing fauna.

The *British Seas* now deserve attention. They are greatly influenced by the Irish branch of the Florida Current. The main current towards our islands is in a northerly direction. The coasts of the South of Ireland and West Wales are washed by waters of the Florida Current, which has come in an easterly direction from the Newfoundland Banks.

The Lancashire Sea Fisheries Committee set out 1,045 drift-bottles up to 1896, of which 440, or 42 per cent., were recovered. The results of these experiments are complicated by two factors, tidal streams and prevailing winds. For instance, many bottles set free off the Lancashire coast in prevailing easterly winds in spring drifted across to the Irish coast. Probably more water passes out of the Irish Sea through the North Channel than enters that way, and more water enters by St. George's Channel than passes out that way, and there is consequently a slow current, irrespective of tides, flowing from south to north in this area. But in an area

like the *Irish Sea,* where the tidal currents are very strong, long series of observations are necessary in order to determine what current remains when tidal streams have been eliminated.

According to drift-bottle experiments there is a current running east in the English Channel, but the International investigations show that there are considerable differences from year to year. There are pulsations of the Florida Current which result in a very different influx of oceanic water into our seas from year to year. The detailed description of the annual variations in salinity and temperature in the British seas is beyond the scope of this work, and reference should be made to the numerous reports of the International Council for the Exploration of the Seas. It may be remarked that these variations are accompanied by a change in the plankton. In August, 1905, water of high salinity (over 36 per mille) entered the English Channel, and at the same time large swarms of pteropods, which are of oceanic habit, appeared in the Channel and even in Plymouth Sound.

The east-going current in the English Channel, after allowing for the influence of the tidal streams, must be slight. The coastal plankton predominates and rapidly overcomes the introduced oceanic species, although there are notable exceptions, as in 1903, when the diatom *Ceratium tripos* rapidly extended from the Lyme Regis-Guernsey line in May to Dungeness in November. On the French coast the general drift is to the east, and the coastal drift of sand and pebbles confirms this. There may be at certain times of the year a westerly drift in the northern part of the entrance to the Channel, and there seems reason to believe that a certain amount of water leaves the Channel here and flows west and north-west round the Lizard and Land's End. Northerly currents have been determined along the north coasts of Devon and Cornwall, and Gough states that a planktonic Siphonophore (*Muggiæa atlantica*) drifts across from the neighbourhood of Land's End towards the Smalls and thence to the Irish coast, and then south and west to the Fastnet.

In the *North Sea* the currents are divided into two main groups by the parallel of 53° N. Lat.; but here also there are similar variations in the nature and origin of the water, depending on the strength of the "pulsation" of the Florida Current. It is difficult to take any year and describe the conditions as typical, since our observations require considerable

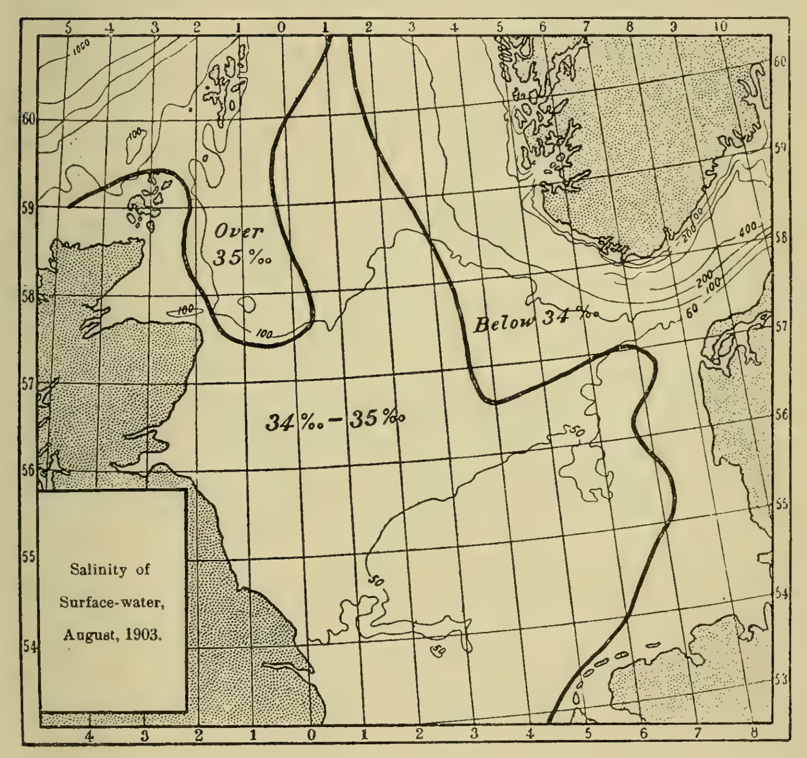


FIG. 35.—NORTH SEA SALINITIES, AUGUST, 1903.

extension before such a statement can be made. Broadly speaking, water of fairly high salinity (over 35 per mille) enters the North Sea both from the north and the south, and the extension of this water varies in different months and again from year to year. In August, 1903 (see Fig. 35), the greater part of the North Sea was covered with water of salinity between 34 and 35 per mille. This may be considered as

North Sea water proper. To the eastward there is a wide margin of water below 34 per mille; this is Bank water, and results from a mixture of the North Sea water with fresh water from the continental rivers and the outflowing Baltic Current.

Atlantic water is present in the northern portion of the North Sea—that is, the branch of the Florida Current has

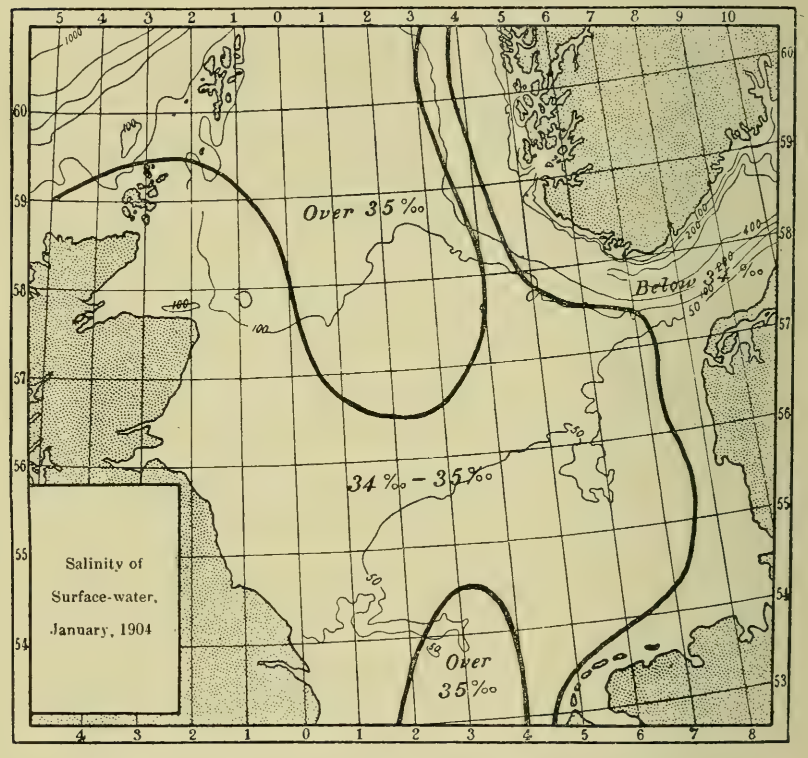


FIG. 36.—NORTH SEA SALINITIES, JANUARY, 1904.

come round the north of Scotland and covers the deep part of the North Sea north of the Dogger. There is no Atlantic water north of 53°.

In January, 1904, the northern tongue of Atlantic water proceeding from the Faroe-Shetland Channel has become much larger, and towards the south the Atlantic water which

has entered through the English Channel is visible. In March a further flooding by Atlantic water has taken place.

The influx of water, therefore, may be considered to commence in August, and reach its maximum in the following spring. After that its area diminishes. Drift-bottle experiments in the North Sea have been made by the Scottish

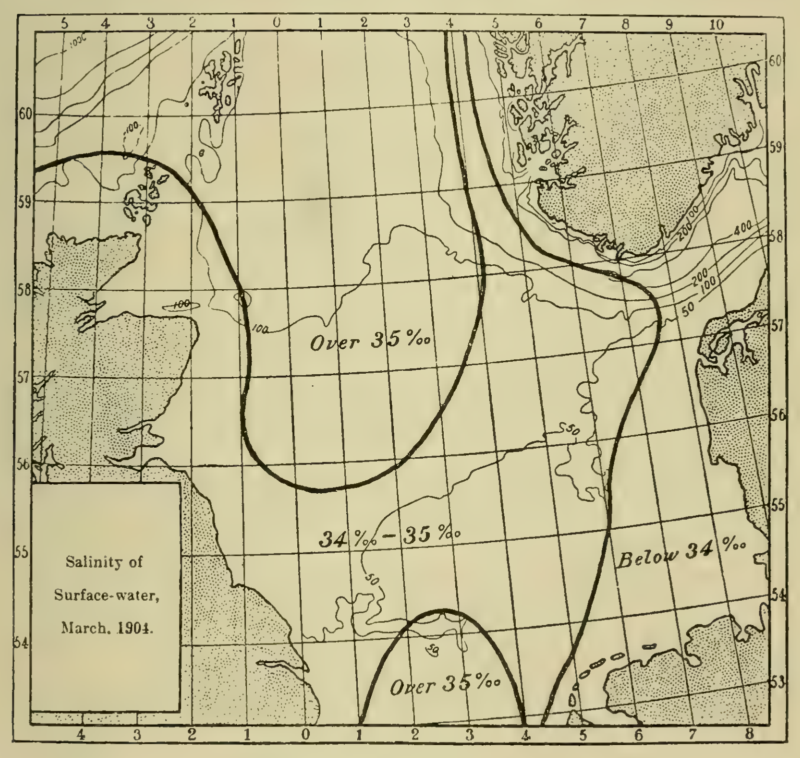


FIG. 37.—NORTH SEA SALINITIES, MARCH, 1904.

Fishery Board between September, 1894, to the spring, 1897. According to Fulton, 3,553 bottles were set free, some from fishing boats, others from steamers from Leith to Christiansund, Hamburg and Rotterdam. Of these, about one-sixth (572) were subsequently recovered. Their drift is shown in Fig. 38. Those liberated on the English side were mainly recovered north of Flamborough Head, many from the west

coast of Jutland, and comparatively few from the Dutch and German coasts. A few reached Norway. The text figure shows the drift clearly; it is in a counter-clockwise direction, and the current deviates from the English coast near the latitude of 54° N. and runs thence eastward to the Horn's Reef, taking the south side of the Dogger. With strong

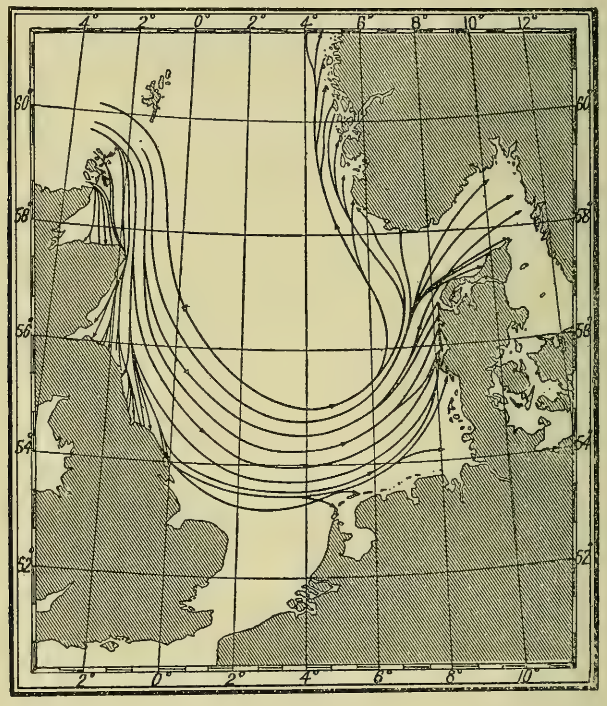


FIG. 38.—DRIFT-BOTTLE EXPERIMENTS IN THE NORTH SEA. (AFTER FULTON.)

prevailing winds some of the bottles made 12 miles per day, but the greater number only 2 to 3 miles. The current is clearly dependent to a large extent on the wind. This is confirmed by the fact that many bottles set out on the Leith-Hamburg line in December, 1896, and January, 1897, when strong easterly winds prevailed, drifted across to the coasts of Norfolk and even Northumberland.

A Belgian drift-bottle experiment was carried out by Gilson off the West Hinder Lightship, 20 miles west-north-west from Ostend. From December, 1899, on the first day of each month for 18 months 100 bottles were set out, half with the flood-tide and half with the ebb. The bottles drifted almost exclusively north-east towards the German coast, some even reaching Jutland and South Norway.

Gilson deduced from his experiments that the currents in this region of the North Sea were directly dependent on the winds.

Current observations have also been made from the Dutch lightships in the North Sea of late years by Van der Stok. The results were analysed and the tidal streams eliminated, so that what remained was attributed to the North Sea Current.

NORTH SEA CURRENTS, 1898–1899.

Results of Observations from Dutch Lightships.

Lightship.	N. Lat.	E. Long.	Average Direction.	Velocity in Centimetres per Second.
Noord-Hinder ...	51° 35′	2° 37′	N. 21° E.	2·24
Schouwenbank ...	51° 47′	3° 27′	N. 33° E.	4·92
Maas	52° 01′	3° 54′	N. 11° E.	6·20
Haaks	52° 58′	4° 18′	N. 2° E.	7·00
Terschelling Bank	53° 27′	4° 52′	N. 54° E.	5·84

N.B.—5 centimetres per second is equivalent to one-tenth of a knot.

At the first two lightships the current is influenced in direction by the presence of narrow banks in the vicinity; at the others the current runs seaward from the coast. The increase in velocity northward at the first four stations is attributable to the influence of the mouths of the Rhine and other rivers. At the three northern lightships the influence of the spring flooding of the Rhine is clearly discernible, since from April to July the velocity increases much beyond the annual average. At the Maas in April it is 8·57 centimetres per second, at Haaks 8·84 in July, and at Terschelling Bank 10·93 in April.

Similar results were obtained by Miss Kirstine Smith at the Danish lightships Horns Riff and Vyl (west of Esbjerg). Here, again, when the influence of the tidal currents was eliminated, there remains over a current which runs along the reef, following the 20-metre line. Miss Smith obtained the following results in 1904:

NORTH SEA CURRENTS.

Danish Lightships, 1904.

Lightship.	N. Lat.	E Long.	Direction.	Velocity in Centimetres per Second.
Vyl	55° 23′	7° 45′	N.W.	10·0
Horns Riff	55° 34′	7° 19′	N.N.W.	20·5

N.B.—20·5 centimetres per second is about four-tenths of a knot.

The currents in the Norwegian Deep and the Skager-Rack are determined mainly by the outflowing Baltic Current. Water of low salinity pours out of the Baltic through the Sound, where it runs up along the Swedish side of the Cattegat, forced there by the prevailing west wind and the earth's rotation. At distances of 4 to 6 miles from the land its velocity is from 24 to 48 miles per day. Even the latter total is exceeded in south-west gales. The current here runs against the prevailing wind. This strong northerly current runs up to the Norwegian coast, then it runs west away from the land. Off the Norwegian coast the current receives a good deal of fresh water from the Norwegian fiords, this further reducing its salinity. It is estimated that the sea-level here (between Lindesnaes and Christiania) is 60 centimetres above that north of the Shetlands. So the Baltic Current is well marked over the Norwegian Deep right up to Haugesund, where it is continued as the Norwegian coastal current. On the Bohuslan coast the herrings come in to spawn in the winter months at the same time as the Bank water of 32 to 33 per mille salinity. When this Bank water is forced out by colder

and less salt water from the Baltic the herring disappear into deeper and warmer water, where they are immune from the local fishermen.

The Baltic Current has a yearly periodicity depending on the drainage of fresh water from the land into the Baltic. The maximum is in summer. Even in May the whole surface of the Skager-Rack is covered with a thin layer of Baltic water. In autumn this begins to recede, and at the end of winter the Baltic Current is only felt as a narrow coastal stream, along the Bohuslan and Norwegian shoals. Here, again, the prevailing winds can cause marked deviations from the normal direction and strength of the current.

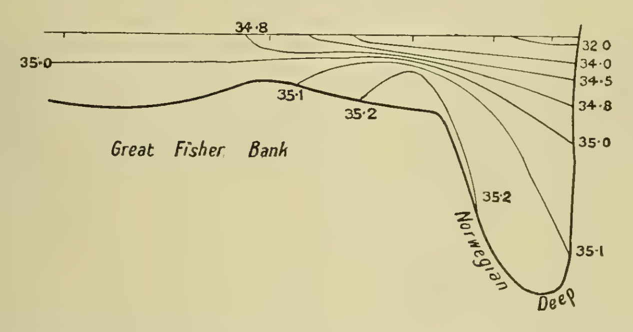


FIG. 39.—ISOHALINES IN THE NORTH SEA. (FROM KNUDSEN.)
Section south-west from Ekersund.

With regard to the deeper currents in the North Sea their prevailing direction is an easterly one. This is shown by the water of high salinity found in the Norwegian Deep. The general direction of the isohalines shows that the bottom current must run in a south-easterly direction.

Experiments have been carried on by the Scottish Fishery Board with "bottom trailers," strong glass bottles so weighted as to drift along or just clear of the bottom of the sea. From the North of Scotland and the Orkney Islands there is a drift of the bottom water to the eastward to the North Sea banks.

The currents of the *Baltic Sea* depend to a large extent on the wind, but also the increase and decrease of fresh water

from the land plays an important part. Atmospheric pressure is also of importance. The relation of wind to current at the exit of the Baltic is seen from the following table, which is the result of 5,918 observations at the Gjedser Riff Lightship off Falster Island.

WIND AND CURRENT AT GJEDSER RIFF.

	Wind from East.	Wind from West.	Calm.	Observations.		
	Per Cent.	Per Cent.	Per Cent.			Per Cent
Current to east ...	14	38	18	1,736	=	29
Current to west	80	54	82	3,757	=	64
No current ...	6	7	0	425	=	7

Even with a westerly wind the outgoing current (*i.e.*, against the wind) predominates; the outgoing current is still more remarkable during calms. As to the yearly periodicity, the outgoing stream is most frequent in spring, when it constitutes 76 per cent. of the observations, this, of course, being the period when the fresh water from the land is at its maximum and the prevailing winds are from the east. In summer the frequency sinks to 60·5 per cent.; at this time westerly winds are common. In autumn the percentage is 71 and in winter 69. The currents are at times very strong. In the Belt they attain a velocity of 3 to 4 miles an hour. The average at Gjedser is 0·15 knot.

Along the south-east coast of Sweden the current runs south, and thence out through the Sound, Cattegat, and Skager-Rack. On the German coast the current has an easterly trend.

In the *Gulf of Finland* in calm weather the current is westerly, and is composed of water of low salinity. It is a feeble current and runs more to the north or Finnish side of the Gulf. Bottom currents of salter water run in the reverse direction, so that the waters of the Gulf are never quite fresh. The surface salinity is lowest at the commencement of July and highest in winter, when storms stir up the water. Bottom

waters have their maximum salinity at the end of May and beginning of June.

The *Gulf of Bothnia* is to a certain extent separated from the rest of the Baltic by the Aland Islands, so that the Gulf has an independent circulation. East of the Aland Islands the current runs to the north and on the Swedish side to the south out into the Baltic, but the currents are not continuous. With strong winds these currents may be reversed. The bottom currents running into the Gulf are also intermittent. The northerly surface current on the Finland side sends off a number of branches to the Swedish side, but the bottom currents run straight up the Gulf.

The Arctic Currents.

The Arctic "Ocean" is really an enclosed sea. Its currents have been investigated in some detail in recent years; more especially its connection with the North Atlantic has been the object of research on the part of the International Council for the Investigation of the Sea.

The north-eastern branch of the Florida Current ("Gulf Stream") flows across between the Faroes and Shetlands to the Norwegian coast. Then it runs up along this coast past the North Cape, whence it spreads out fan-wise. The southernmost branch, the "North Cape Current," runs along the coast into the Murman Sea; another branch flows to Spitsbergen, where it has been traced to 80° N. Lat. and 10° E. Long.

There is a barometric minimum over the sea in these latitudes, owing to the warm Atlantic water and air, and a maximum over the colder land. This produces a cyclonal movement of the atmosphere, which, owing to the configuration of land and water, tends to force the Atlantic water as far as Nova Zembla. Between Spitsbergen and Franz Joseph Land there is, however, shallow and ice-covered water. Here on the east side of Spitsbergen there is a westerly drift; on the west side of Spitsbergen, on the contrary, a north-easterly

drift of Atlantic water. The fructification of the West Indian *Entada gigalobium** have been found as far north as 80° in longitude 17° 40′ east. These fruits are known to the inhabitants of the Faroes, where they are frequently found on the coast, as "goblin's kidneys." The Norwegian botanists give lists of the tropical plants that have been washed up on the Norwegian coasts by the Florida Current.† One of the most remarkable ocean drifts on record is referred to the "Gulf Stream" and Equatorial Current. In 1822 a vessel was wrecked on Cape Lopez (Gulf of Guinea), its cargo consisting of barrels of palm-oil. A year later one of these barrels, with an unmistakable distinguishing mark on it, was washed up at Hammerfest in Norway, a drift of about 11,000 sea-miles. The warm Florida Current meets in the western portion of the North Atlantic a southerly cold current, with drift ice and icebergs. This current is due, in part at any rate, to the prevailing East Greenland northerly wind, and is a branch or portion of a Polar current which runs from near the Pole to Cape Farewell. This Polar current averages 6 miles a day; near the coast in shallow water somewhat less; at its eastern boundary up to 20 miles per day—*i.e.*, in Denmark Straits. It is weakened by southerly, but strengthened by northerly winds. To the north of Iceland the water movements are affected by the prevailing anticyclonal atmospheric conditions over the island, and also by the presence of fresh water derived from the land. Numerous investigations have recently been carried out on the currents in the extreme North Atlantic by the Norwegian scientists, and for further details the works of Nansen, Helland-Hansen, Knudsen, and Pettersson should be consulted.

Put briefly, there is a current of cold water running round the north and east of Iceland. This "East Iceland Current" is a branch of the East Greenland Current, and brings with it pack-ice, drift-wood, and occasionally icebergs, into this part

* A leguminous climbing shrub (suborder Mimosæ) remarkable for its large pods.

† Schübeler and Ingvarson.

of the Atlantic. Probably the icebergs seen by James Ross in 1836 in 61° N. and 6° W. came from this current. At any rate, the current produces a tongue of cold water of low salinity (under 34) north of the Faroes (Fig. 40).

Between this water and that of the Florida Current (over

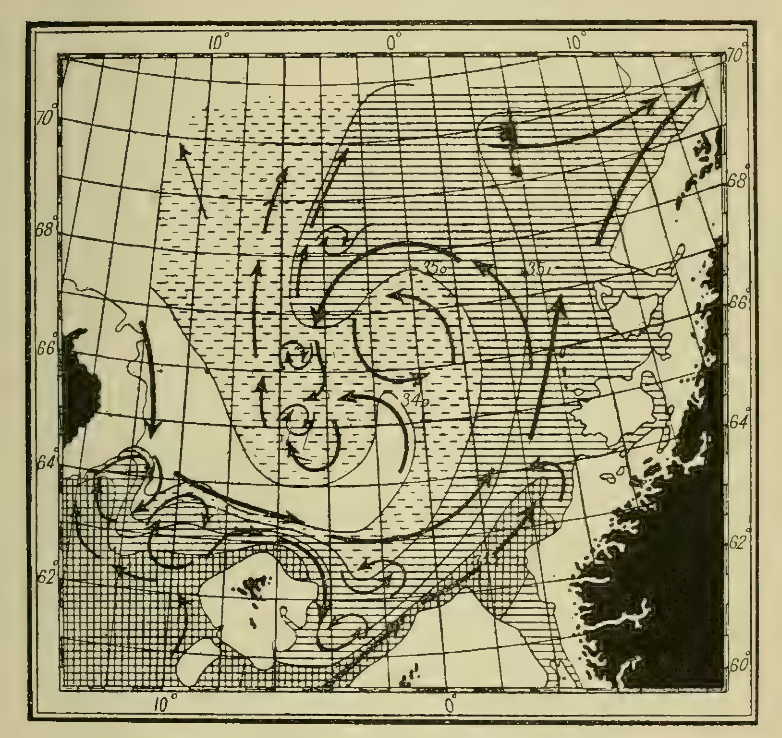


FIG. 40.—SURFACE CURRENTS AND SALINITIES AT 150 FATHOMS IN THE NORWEGIAN SEA. (HELLAND-HANSEN AND NANSEN.)

35 salinity) there is a body of mixed water (between 35 and 34 salinity) with varying and often whirlpool circulation.

The distribution of this water probably varies from year to year, certainly the extent of the cold tongue varies; the figure shows the average conditions during 1900-1904. According to the biologists, the chief species of Copepod characteristic of the different masses of water is for the east part of the cold tongue *Calanus hyperboreus;* for the mixed water *Calanus*

finmarchicus; and for the Atlantic water in the north *Pseudocalanus.*

The Norwegian coastal current runs up along the coast in the same general direction as the Florida Current. It is a prolongation of the current coming from the Baltic, with the addition of a considerable volume of land water. Its velocity is weak, reaching in summer only 5 to 6 miles a day; in winter, with prevailing south-west winds, its velocity increases. The pulsations of the Florida Current have already been mentioned. In some years the current runs stronger, in other years weaker, and the variation of the current influences the climate of the British Isles and the Scandinavian peninsula to a marked degree. In particular Pettersson has investigated the correlation between the oceanic circulation and the climate and agriculture of Norway. The temperature of the sea-water off the Norwegian lighthouses is connected with the blossoming of the coltsfoot (*Tussilago farfara*) in Central Sweden. In earlier years only these coastal temperatures were available, but since 1900, owing to the International Fishery Investigations, we have records of the extent of the Florida Current drift in Norwegian and other North Atlantic waters. The study of the records made on a line west from the Sognefiord (Norway) and a comparison with the growth of land plants is interesting. The growth of the Norwegian pine for the following year and the autumn crops of barley and legumes depend on the sea temperature. A high temperature of the Atlantic drift-water in May is followed by a good yield of the autumn crops on shore, as well as by an early spawning of the cod on the Lofoten Banks in the following spring and a diminution of the pack-ice in Barents Sea two years later.

There is a somewhat similar circulation to that shown in the sketch (Fig. 41) north of Jan Mayen. The East Greenland Current sends out a tongue of cold water of 34·8 per mille salinity and $-1·3°$ C. temperature. In this area the Norwegian hunters every March capture large numbers of the Greenland seal (*Phoca grœnlandica*). The Atlantic Current

runs up the west side of Spitsbergen, at the northern extremity of which it divides into three main branches running north and north-east, but mainly to the west. There is a mixture of water between the warm Atlantic Current and the cold East Greenland Current, with, on the whole, a cyclonal circulation. It was along the western edge of this cold current (in about

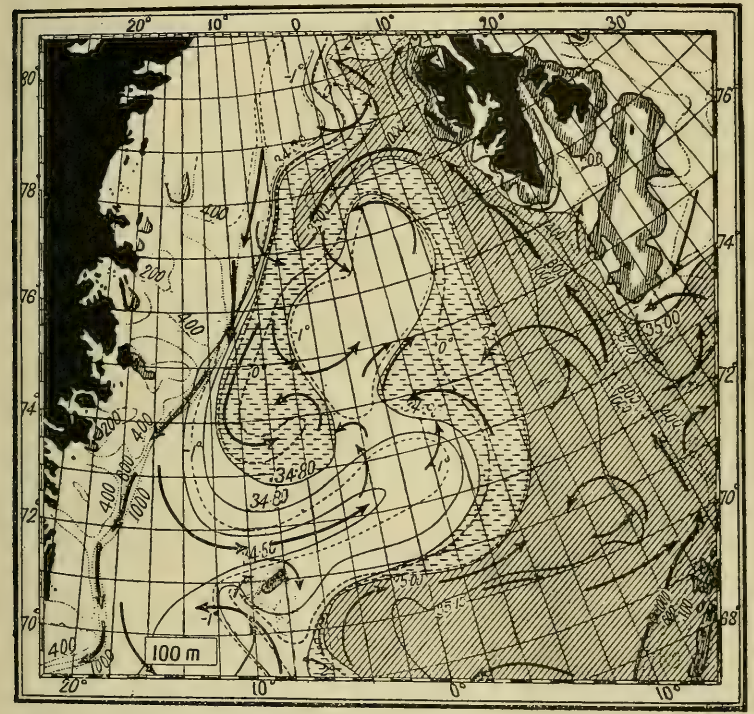


FIG. 41.—SURFACE CURRENTS AND SALINITIES IN THE GREENLAND–NORWAY AREA. (HELLAND-HANSEN AND NANSEN.)

79° N.) that the Spitsbergen whalers hunted the whale after the first period of the bay whale fishery was over (*i.e.*, from 1623 onwards).* This East Greenland Current, in its surface layers at least, consists for the main part of land water derived from the North Asiatic and North American rivers.

The Florida Current flows into Barents Sea. It is now

* J. T. Jenkins, "A Short History of the Whale Fisheries."

known as the North Cape Current, and it runs across along the Murman coast, ultimately sinking, owing to its higher salinity, below the colder Arctic waters. In the bottom waters of Barents Sea one finds large shoals of edible fish of commercial value—*e.g.*, the plaice. These grounds are the northernmost frequented by British trawlers, which have fished here since 1905.* It has been identified as a bottom layer by Nansen on the *Fram*, to the south of Nova Zembla. The glass globes used by the Norwegian fishermen on their drift-nets are frequently detached from their nets in storms and drift across in the North Cape Current to the Murman coast as far as the Petschora estuary. Another branch of the current is found on the bottom between Nova Zembla and Franz Joseph Land, and still another between Franz Joseph Land and Spitsbergen.

A branch of a cold Polar current runs south-west to Bear Island, which is consequently frequently blocked with ice, though land in much higher latitudes—*e.g.*, Spitsbergen—may at the same time be ice-free. This Bear Island Current originates in Barents Sea, but has not much strength and does not overlap the island much.

Farther east in Kara Sea and beyond the Liakov or New Siberian Islands there is a general westerly drift, except, perhaps, in the immediate neighbourhood of the coasts, where it is easterly at first. Owing to land water and precipitation, the sea-level in the Arctic is probably higher than in the Atlantic, and consequently water flows out somewhere from the former to the latter. The main exit is the East Greenland Current. On this general westerly drift across the Pole Nansen based his hopes of reaching the Pole on the *Fram*. Prior to this, the *Jeanette* was wrecked in June, 1881, in 77·6° N. Lat. near Henrietta Island (North Siberia), and its relics found in 1884 near Julianshaab, in South-Western Greenland.

Confirmation of this drift is afforded by the experiments

* See J. T. Jenkins, "The Sea Fisheries," 1920, p. 32. London: Constable.

of the American Admiral Melville, who prepared fifty spindle-shaped buoys, which were set out by whalers in the summers of 1899 and 1901 in Beaufort Sea and near Wrangel Island.

Four of these were recovered—two near the locality of liberation; one drifted from Cape Barrow (North America), September 13, 1899, to the north coast of Iceland (June 7, 1905); the other from the mouth of the Mackenzie River near Cape Bathurst to the Norwegian coast near Hammerfest.

Siberian timber frequently drifts across the Polar basin to the north of Spitsbergen or to the East Greenland coast. Nathorst collected drift timber in 1898 and 1899 on Bear Island, Spitsbergen, Jan Mayen, and East Greenland, and by far the greater proportion was found to be of Siberian origin.

The Pacific Currents.

There are North and South Equatorial Currents and an Equatorial Counter-Current, as in the Atlantic.

The North Equatorial Current is a westerly drift caused by the north-east trade winds, and it covers the whole stretch of the North Pacific from the Revilla Gigedos Islands (Mexico) to the Philippines, a distance of 7,500 sea-miles. The southern boundary lies in summer in 10° N. Lat. and in winter in 5° N. Like the corresponding current in the Atlantic, the velocity is slight, averaging 12 to 18 sea-miles per day. This current bends through the Balingtang Channel into the China Sea; part of it flows round both sides of the island of Formosa to take part in the Japanese (Kuro Siwo) Current.

The South Equatorial Current also resembles the corresponding current in the Atlantic, like which it attains its greatest velocity on and just north of the Equator. The Southern Equatorial Current is stronger than the Northern, 20 miles per day being the average, though much higher velocities, up to 100 miles per day, have been recorded. It stretches from 85° W. Long. to 135° E. Long., a distance of 8,500 miles, so that it is three or four times as long as the corresponding Atlantic Current. A branch runs through

Torres Straits, another south along the east coast of Australia.

In the southern summer the south-east trades only prevail between the Peruvian coast and the Marquesas Islands, so the current is somewhat modified in its eastern branches.

The Equatorial Counter-Current runs in an easterly direction between the two above—from Mindanao and Gilolo

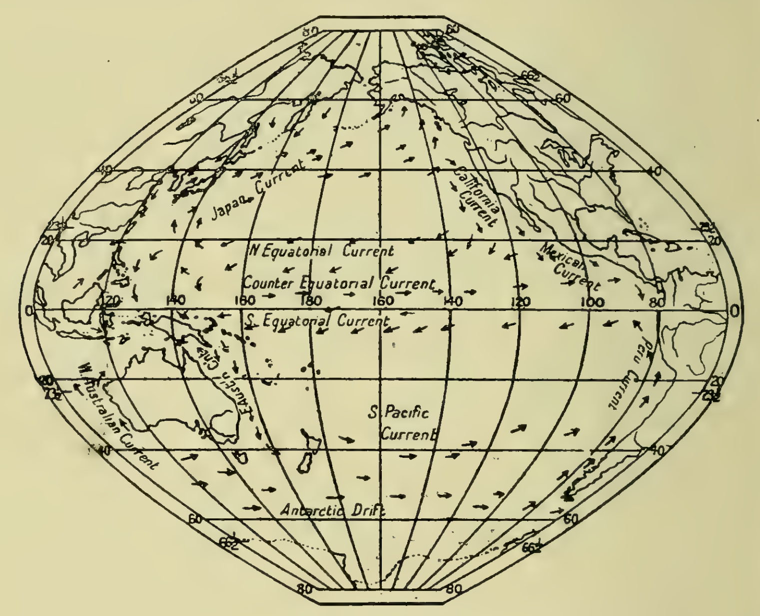


Fig. 42.—Currents of the Pacific Ocean.

in the west to the Gulf of Panama. Like the Guinea Current in the Atlantic and the Equatorial Counter-Current in the Indian Ocean, the Equatorial Counter-Current of the Pacific is a compensation stream. It sends off a branch in the Gulf of Panama to the southward.

The Japan Current is the prolongation of the North Equatorial Current in a northerly and north-easterly direction.

In winter the current bends to the north at the northern extremity of Luzon, passes Formosa on the east side, where it

has a breadth of 100 miles and a direction north-north-east. It leaves the Loo-choo Islands to the right, and flows on past the Japanese coast, where it is known as the Kuro Siwo Current (Blue Salt Stream), after which it curves to the eastward, following the general easterly drift of the North Pacific. It is now known as the North Pacific Current, or Kuro Siwo Current, or West Wind Drift, and is of considerable interest, since it throws some light on the possibilities of the connection between the aborigines of North America and Asia.

In 1815 the brig *Forester* of London sighted a Japanese junk 350 miles off Cape Conception, seventeen months after it had left Osaka. Three of the crew of the junk were still alive.

In 1832 a similar junk reached Oahu in the Sandwich Isles; in 1833 another was stranded at Cape Flattery (Oregon).

Wilkes records that in 1833 a Japanese junk drifted ashore at Port Grenville (Vancouver), the three surviving members of the crew being made slaves by the Indians.

When the North Pacific Current strikes the American coast it divides into two branches, running north and south respectively along the coast. The north-going current enters Alaskan waters as relatively warm water, carrying with it Asiatic drift-wood, which becomes stranded on the Alaskan coast and the Aleutian Islands. The southern current is the Californian or Mexican Coast Current. It is a cold current, water of low temperature welling up from the depths off the coast.

The East Australian Current runs south along the east coast of Australia, although the prevailing winds are north-east in summer and south-west in winter. In 40° S. Lat. it bends to the east.

There is a great easterly current running right across the South Pacific from Tasmania to the South American coast. It receives some tropical water from the East Australian Current. It runs from Tasmania south of New Zealand in about 50° S. Lat., and is unquestionably a continuation of the easterly current of the Southern Indian Ocean.

When this easterly current of the South Pacific reaches the American coast in about 45° S. Lat. it splits into two branches, one of which, running south round Cape Horn, is the Cape Horn Current, which runs south, south-east, east, and then east-north-east, and finally is continued as the Falkland Current in the Atlantic.

The second branch runs north as the Peruvian or Humboldt Current. This is a cold current, and is clearly due to the deflection of the prevailing easterly drift by the land. It is a feeble current, and can be reversed by the northerly winds. The prevailing winds here, however, are from the south. In 5° S. Lat. it leaves the coast and flows north-west into the South Equatorial Current.

From Bering Sea, on the west side, a cold current runs down past Kamtchatka and the Kuriles to Japan. This is the Oya Siwo Current; off the west of Japan the coastal water is only 2° or 3° less than the Kuro Siwo, and its colour pale (according to some observers) or dark (according to others) green.

Cold water is only met with on the east side, north from 37° or 38° N. Lat., where in February, near the land, sailing ships in an hour notice a drop in the water temperature from 16° to 6° C. The Oya Siwo comes from the north-east.

Indian Ocean.

The Indian Ocean currents differ from those of the two other oceans in that they change with the seasons—the north-east and south-west monsoons. At least two charts are necessary for the delineation of these currents; better still are the monthly charts published by the British Admiralty.

The currents in the northern section of the Indian Ocean—*i.e.*, in the Arabian Sea and the Bay of Bengal—run with the prevailing winds. There is a general westerly drift, corresponding to the North Equatorial Current of the Atlantic. This runs from the Andamans to the Somali coast in winter. There is also a South Equatorial Current, running westerly

between 10 and 27 south in winter, but farther north—*i.e.*, up to 5° S. Lat.—in the northern summer. There is an Equatorial counter-current in winter, running easterly from 2° to 5° S. Lat.; this disappears in the northern summer.

At the period of the south-west monsoon the general drift of the currents in the Northern Indian Ocean is easterly, and this tendency is felt in the Red Sea as far as the Suez Canal, so that Mediterranean water enters the Red Sea at this time. Water flows out through the Gulf of Aden into the Arabian Sea.

The Indian South Equatorial Current strikes the island of Madagascar, where it splits into branches in about 10° S. Lat., one running south along the coast as the Mozambique Current, ultimately becoming, south of 30° S. Lat., the Agulhas Current. South of the Tropic of Capricorn this current bends to the east, and merges into the South Atlantic easterly current. Where the Agulhas Current merges into the colder water of the South Atlantic drift there are frequent changes recorded in the surface temperatures.

Running up the western side of Australia is the West Australian Current, analogous to the Benguela Current of the Atlantic. Far south there is an easterly current which is a continuation of the general Antarctic drift. Drift-bottles set free off Cape Horn have been found on the south coast of Australia and the west coast of New Zealand. One such bottle drifted from the southern part of the Brazil Current to the north of New Zealand in three and a half years, a distance of 10,700 sea-miles. It is more than likely that there is a current right round the world in these latitudes.

APPENDICES

APPENDIX I

Conversion Tables

(a) Fathoms and Metres.

One fathom = 1·828 metres. Approximate equivalents are:

Fathoms.	Metres.
5	9
10	18
50	91
100	183
200	366
500	914
1,000	1,829
2,000	3,658
2,500	4,572

Metres.	Fathoms.
5	2·73
10	5·47
50	27·3
100	54·7
200	109·4
500	273·4
1,000	546·8
2,000	1093·6
2,500	1367·0

(b) Marine Distances.

One sea-mile is 6,080 feet, or 1·852 kilometres.

A cable's length is 8 shackles, or 100 fathoms (strictly 202·7 yards).

A knot is a unit of *speed,* and is a speed of 6,080 feet per hour. It is incorrect to speak of "knots per hour."

On the assumption that the earth is a sphere, the length of an arc of a meridian subtending an angle of one minute at the centre is 6,077 feet; the nearest whole number to this, 6,080 feet, has been taken as the length of the mean nautical mile.

(*c*) *Temperatures.*

$$\frac{F-32}{9}=\frac{C}{5}=\frac{R}{4}.$$

(*d*) *Velocities.*

Centimetres per Second.	Knots.
10	0·19
50	0·97
100	1·94
250	4·86

Knots.	Centimetres per Second.
1	51
5	257
10	514
15	771

APPENDIX II

Bibliography

The Government of the United States first proposed a uniform system of observations at sea at a conference held at Brussels in 1853, which was attended by representatives of the leading maritime nations. A log-book for vessels recording meteorological and other data was decided on, and this has remained in force, with slight alterations in 1873, to the present day.

This log contains, in addition to the daily position of the ship, notes on the weather, such as direction and force of wind, temperature of the air, barometric pressure, clouds, sea temperature, specific gravity, waves—their direction and strength. Many millions of these log-books, from all the seas of the world, are now accumulated in the various central offices of the different Governments which have a large mercantile marine.

Considerable research into oceanographical conditions can be carried on without going to sea, and, in fact, many important publications have resulted from a study of these and similar journals. Much of this material has been utilised, and

the publications of the Meteorological Office and the Hydrographic Office at the Admiralty bear witness to this.

The Meteorological Office publish a "Marine Observer's Handbook," which gives a list of these publications.

There is also a "Seaman's Handbook of Meteorology," a companion to the barometer manual for the use of seamen, which contains not only a description of the meteorological instruments most commonly in use on shipboard, but also an excellent chapter on icebergs and other forms of drifting ice.

The North Atlantic is now divided up into one-degree squares for indicating the position of ships sending weather reports by radiotelegraphy. These messages are synchronised, the time of despatch depending on the vessel's position in the North Atlantic. The messages are received at the Meteorological Office in London the same evening, and are used as a basis of the weather forecast for the following day.

Textbooks.

There is no suitable textbook in the English language on the subject. The best introduction is that by Sir John Murray in his book, "The Ocean," published by Williams and Norgate in the Home University Library.

Maury's "Physical Geography of the Sea and its Meteorology," published by Sampson, Son and Co., tenth edition, dated 1861, is a good book, but hopelessly out of date, and therefore dangerous for beginners. It is of good historical interest, since it contains the earliest maps with isothermal lines for the ocean surface. Murray and Hjort's "Depths of the Ocean" contains a good account of the conditions in the North Atlantic, and is suitable for advanced students.

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"Three Cruises of the Blake," by Alexander Agassiz. *Bulletin Mus. Comp. Zool.*, vol. xiv. Cambridge, Mass., U.S.A. 1888.

Challenger Reports: "Narrative of the Cruise, Deep-Sea Deposits, Oceanic Circulation, and Summary of Results." 1885-1895.

Report on Norwegian Fishery and Marine Investigations. Helland-Hansen and Nansen. Bergen. 1909.

There are, of course, many others. The above serve as useful types for an introduction to the subject.

The *Challenger* Society (Secretary, Mr. Tate Regan, F.R.S., Natural History Museum, South Kensington, London, S.W.) publishes charts and books of interest to oceanographers.

Tides.

In many respects this is the most difficult branch of the subject. For the beginner a consideration of the simpler phenomena is sufficient. Further information may be sought in—

Airy: "On Tides and Waves," in the *Encyclopædia Metropolitana*, vol. v. London, 1842. (The treatment is mathematical.)

Rollin A. Harris: "Manual of the Tides." U.S. Coast and Geodetic Survey. (A voluminous work.)

W. H. Wheeler: "A Practical Manual of Tides and Waves." London, 1906.

Biology of the Sea.

"Conditions of Life in the Sea," by J. Johnstone. Cambridge Biological Series. 1908.

General Hydrography.

The publications of the International Council for the Exploration of the North and Neighbouring Seas from a Fishery Standpoint should be consulted, particularly "Conseil permanent international pour l'exploration de la mer. Publications de circonstance." A series of short descriptive monographs in English, French, and German.



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